UNION GÉODÉSIQUE ET GÉOPHYSIQUE INTERNATIONALE
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ASSOCIATION INTERNATIONALE
D'HYDROLOGIE SCIENTIFIQUE

INTERNATIONAL ASSOCIATION
OF SCIENTIFIC HYDROLOGY

COLLOQUE D' ATHENES

10-9 — 18-9 1961

SYMPOSIUM OF ATHENS

EAUX SOUTERRAINES DANS LES ZONES ARIDES
GROUNDWATER IN ARID ZONES

TOME II — VOLUME II

PUBLIÉ AVEC L'AIDE FINANCIÈRE DE L'UNESCO

PRIX : 250 Frs belges

PUBLICATION N° 57
DE L'ASSOCIATION INTERNATIONALE D'HYDROLOGIE SCIENTIFIQUE
SECRÉTAIRE : L.J. TISON
BRAAMSTRAAT 61, (RUE DES RONCES)
GENTBRUGGE (BELGIQUE)
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VUES GÉNÉRALES SUR LA MISE EN EXPLOITATION DES RESSOURCES

GENERAL VIEWS ON THE DEVELOPMENT OF GROUND WATER RESOURCES

PLANNING FOR GROUND WATER DEVELOPMENT

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RÉSUMÉ

Le développement des bassins aquifères dans les régions arides et semi-arides du monde constituent souvent le moyen le plus important d'obtenir l'utilisation optimum des ressources en eau. Les nombreuses disciplines scientifiques et techniques intervenant dans les études logiques des recherches des ressources en eau sont discutées et les relations complexes des phénomènes hydrologiques sont décrites. Les lignes générales des recherches et des indications de résultats probables qui doivent être atteintes pour un planning convenable sont exposées. La discussion est divisée en envisageant des bassins vierges, non exploités, des bassins en exploitation partielle (exploitation utile égale à la recharge) et des bassins complètement exploités où l'alimentation naturelle est complètée par une recharge artificielle et par l'adjonction d'une utilisation d'eau de surface.

SYNOPSIS

The development of ground water basins in arid and semi-arid areas of the world will often constitute the most important means of attaining optimum utilization of the available water resources. The many scientific and technical disciplines involved in comprehensive water resource studies are discussed and the complex interrelationships of hydrologic phenomena are described. General outlines of required investigations and indications of probable results to be attained from proper planning are given. The discussion is divided with respect to basins in a natural (virgin) condition; in a condition of partial development (beneficial use equal to natural recharge); and fully developed basins, where the natural supply is augmented by artificial recharge and conjunctive operation with surface water supply development.

1. GENERAL CONSIDERATIONS

The ever-increasing demands for additional water supply development have resulted in an intensified interest in, and appreciation of, the utility of ground water storage for conserving, regulating, and distributing an appreciable portion of the quantities of water required for maintenance of the expanding standard of living. This, in turn, demands full knowledge of the operational characteristics and capabilities of the underground reservoirs, particularly the alluvial valley fills common to many of the arid portions of the earth. The term arid, as used in this discussion, denotes those portions of the earth's surface where the climatic conditions, insofar as precipitation is concerned, are such that little or no precipitation is available during the normal crop production period.

Suitable surface locations for the conservation and control of water supplies are diminishing in number as development of such sites progresses. At the same time agricultural, domestic, and recreational land uses are impinging on the remaining sites at a rapid rate. Increasing construction costs for major water control structures, and the inherent waste in dissipating costly supplies through evaporation, combine to enhance the natural advantages of utilizing available underground storage capacity for cyclic storage and regulation of the vast supplies of water required to maintain human life on this planet.

Utilization of ground water reservoirs for the maximum benefit to the area involved is dependent upon adequate geologic and hydrologic data, from which the results to be expected as a consequence of development can be estimated. Prerequisite to the full development of ground water storage is adequate technical information, including the basic data required for application of proved hydrologic principles. Required data can be secured by a continuing program for measurement of the quantity of water passing through each phase of the hydrologic cycle. With adequate hydrologic data, reliable estimates of the quantity of water that can be made available on a firm annual basis by coordinated or conjunctive operation of surface and subsurface storage or, alternatively, by operation of the ground water basin alone, can be formulated.

Where development of ground water supplies has resulted in declining yields, increasing pumping lifts, or encroachment of unusable water, hydrologic and geologic investigation is essential to the development of corrective measures and the formulation of a physical solution to the problem. Ground water constitutes a phase of the hydrologic cycle, and research into its relationship with other phases in specific locations is important to the development of all water resources. Effective planning for use is based upon knowledge and development of the total available water resources. An adequate understanding of the ground water phase of the hydrologic cycle requires. development of data concerning precipitation, infiltration, soil moisture, evapotranspiration, and stream flow, as well as the structural characteristics of the subsurface aquifers.

Investigation of physical situations affecting ground water will generally be conducted along three broad fronts, or phases, of inquiry. These phases are not characterized by definite boundaries, but rather shade from one into the other in a complex pattern of skills and knowledge. One such area of research may be termed the geological phase, in which the conditions to be encountered on and under the surface are determined. The primary requisite is the location of underground storage space, which may be found in geological formations containing inherent voids in sufficient volume to hold, transmit, and release water in the quantities necessary to satisfy the demand. Such voids may be solution channels, as in limestone formations; brecciated or fault zones, as in structural unconformities; or interstices between the grains composing the formation. The latter type is ordinarily found in alluvial valley fills and cones, and is composed of gravel or sand, or mixtures of the two, usually interlayered with fine clays or other less permeable material. After determination that usable storage space for practical operation exists, the porosity, transmissibility, chemical composition, location of intake areas, and other basic physical characteristics pertaining to hydrologic and hydraulic operations are determined.

The second field of investigation of subsurface storage areas is the hydrologic phase. This phase is concerned with determinations of water supply available for the project; the regimen of its occurrence; the quality of the native surface, imported, and subsurface waters; the operation of surface facilities for storing, transporting, and for percolating surplus supplies in permeable areas; the recovery of water placed in subsurface storage; and innumerable additional factors bearing on the entire problem of routing water supplies between the place of origin and the place of final disposal.

The economic phase is the third broad field of investigation. This phase is concerned with the determination of places and amounts of use. It involves the classification of land areas as to suitability for irrigated agriculture, domestic, industrial, and other uses; determination of water requirements for the various uses; production, distribution, salvage, and disposal of water supplies made available, and other necessary studies.

It should be understood that the above grouping of phases of ground water supply investigation is made solely for the purpose of convenience in illustration and bears no relation to activities in various fields of endeavor. The engineer and the geologist will function in close coordination throughout the investigation and will be assisted as required by chemists, biologists, physiologists, economists, botanists, attorneys, meteorologists, soil scientists, and other concerned specialists.

After investigation has resulted in determination of the practicability of operations affecting the use of ground water, plans for specific projects can be prepared. Construction of storage, production, transmission, distribution, and salvage or disposal facilities will be followed by operation and maintenance of the system. Here again, the engineer and geologist, assisted by other scientific specialists, have a continuing function in assuring, by constant supervision, the successful operation of the completed project.

Throughout this paper, it will be obvious that the type of ground water basin referred to is the deep alluvial valley fill. In this type of basin, a free ground water surface, subject to atmospheric pressure, and commonly terned the "water table", exists. There are, however, other types of basins, such as the cavernous limestone or sandstone type, and the alluvial type where water is confined beneath a relatively impervious formation. In these latter types, the aquifers possess similarities to enclosed transmission conduits and the water is delivered under pressure. When the withdrawal is at such a rate, however, that pressure is reduced to zero, the aquifers are, in many respects, similar to free ground water reservoirs. Even in pressure type basins, however, there must be an outcrop, or forebay, from which recharge is obtained. The forebays will be, in all respects, similar to free ground water reservoirs, and their ability to regulate the supply will determine the operating yield to be expected from the pressure aquifer. The analysis of pressure aquifers themselves, however, is a subject too broad for inclusion within the confines of the present paper.

The remainder of this paper will be devoted to consideration of the manner and means of accomplishing ground water investigation in areas where the existing stage of development ranges from the natural state to a condition of relatively complete ground water utilization.

2. The Basin in a Natural State

Under natural conditions, a valley area, or plain, underlain by ground water will have established an operational regime in consonance with the prevailing hydrologic and climatic conditions. The surface streams crossing the area will have contributed a portion of their waters to the ground water body through percolation from the stream channel. A portion of the precipitation on the area will also have augmented the quantity of ground water in storage through the process of infiltration and percolation. Once the interstices of the basin material are filled, no further supplies may enter and the basin automatically, through natural forces, establishes a regime of supply and disposal of water which is in accord with the natural characteristics of the region. Ground water moves, under the force of gravity, to the place where disposal occurs. The disposal may be accomplished by evaporation from the surface in swamps, seepage areas, or from the upper soil layers; by vegetative use; by rising seepage to stream or drainage channels; or by subsurface movement from one area to an adjacent, but lower, area. As the water in subsurface storage is depleted, replacement supplies may again enter the basin. Over a long-time period, the quantity entering will just balance the quantity lost through disposal.

Perhaps the maximum quantity will be given up to vegetative use. As the basin gradually fills, water-loving vegetation (phreatophytes) will become established on the surface. This vegetation may at first occupy only a small area of land in the lower surface elevations of the valley or plain. As the ground water table rises, the phreatophyte area will expand in size. Should the expansion be so great as to create a demand for more water than can be provided by percolation from surface streams and precipitation, the water table will fall as a result of the depletion. Consequently, a certain amount of the vegetative cover will wither from lack of water. In the course of time, a fairly definite vegetative area will exist, just sufficient in size to utilize the available water supply. Oases found in many desert areas furnisch examples of this condition of development.

The same balance between average annual supply and vegetative growth will result from cycles of drouth. During drought periods, when surface water supplies and, consequently, the opportunity for, and quantity of, percolation are restricted, the water table will fall as depletion from previously established vegetation occurs. As it falls, some of the vegetation will die and the areal expanse become less. Finally, only that with the deeper roots and combined demand equal to the average annual accretion to supply will survive the dimunition in availability of water.

Although these physical phenomena have been described as if they were separate and independent occurrences, following each other in proper order and appropriate magnitude, such an arrangement does not occur in nature. The complex and continuing interrelationship of all factors affecting ground water supply and disposal cannot be resolved in so simple and definite a manner. An understanding and visualization of the sources of supply and means of disposal, however, is an invaluable aid to judgment when ground water development is considered, in any locality, for the first time.

The initial survey of ground water development possibilities in a hitherto virgin area in beset with many difficulties. Obviously, many of the required data are absent, or exist only in fragmentary form. Records of surface stream flow into and out of the area will provide an indication of the magnitude of loss, or accretion, in flow. Records of precipitation on the surface of the basin, together with observation of the type and extent of vegetative cover will constitute an index of possible recharge stemming from rainfall. Accurate topographic maps are required in order to delineate surface drainage channels and locate areas and features of interest or importance. Geological exploration, including drilling and coring, is necessary to ascertain the arrangement and depth of underground formations and effect laboratory determinations of composition, porosity, specific yield, and permeability of the materials comprising the aquifers. Analyses of the mineral concentrations occurring in the ground and surface waters are necessary to establish the practicability and feasibility of the proposed beneficial uses of the developed waters. Many other associated studies will also be required in order to formulate sound recommendations concerning the proposed development.

Unfortunately, most of the required data will not, or connot, be available in undeveloped areas. It will often be necessary to formulate estimates of the quantities, conditions, or criteria concerned. Surface inflow may be estimated from records secured in similar or adjacent watersheds; from observation of the extent, type, and condition of forest cover in the drainage area; from projection upstream of flow records at a downstream point; from available meteorological data; and from visual evidence of channel conditions and recollections of inhabitants. Percolation opportunity may be judged from observation of the condition, width, composition, and length of surface channels. Precipitation may be estimated from scattered meteorological records, known conditions in other areas, vegetation, evidence of surface drainage channels, and similar indices.

The presence or absence of a ground water table may be inferred from indications of seepage and vegetative growth. The probable depth to the water table may frequently be judged by consideration of the prevailing vegetation. In the western United States, for example, salt grass will send roots to a depth of 10 to 12 feet; greasewood to a depth of between 20 to 30 feet, and mesquite to as much as 50 feet. The amount of water consumed may be estimated by consideration of the density of the growth. In areas where ample supplies are available to such water-loving plants, it has been found that the quantity of water transpired will often lie between 60 and 90 inches of water per year or, on an acre basis, from 5 to 8 acre-feet per acre per year.

There is no feasible substitute for geological reconnaissance and exploration, nor for adequate maps of the area. However, geologic investigation may frequently be deferred until other evidence has indicated the possibility of recovering usable quantities of ground water. Likewise, aerial reconnaissance and photography will compensate, to some extent, for the possible lack of topographic maps. Additionally, since the formation, composition, and location of topographic and geologic features is essentially constant with respect to time, these factors may be uniquely determined during and after the preliminary investigation. No such possibilities exist, however, in the case of hydrologic data, since the measurement not made at the time the phenomena occurs can never be secured at a later data.

However, even with adequate records, and certainly far more so with estimates used in lieu of data, conclusions regarding the utility and adequacy of a proposed ground water operation are, for previously undeveloped areas, qualitative rather than quantitative in nature and must be based upon mature and experienced judgment.

3. THE PARTIALLY DEVELOPED BASIN

In the partially developed basin, defined for the purposes of this paper as one wherein the use of ground water does not exceed the naturally occurring recharge, a considerable development, either agricultural or urban, dependent on use of ground water has taken place. This usually implies that sufficient records of hydrologic and physical phenomena are available, or relevant considerations may be fairly accurately inferred from observation or measurements of existing development. Further development is dependent upon informed interpretation of the facts relating to the existing situation in the area.

Among the classes of data which should be available are records of the depth to the water, or the pressure, surface from which may be constructed contour maps of the ground water surface to aid in the determination of gradients, flows, pumping patterns, underground impediments to movement, and numerous other important operational factors. Other pertinent data includes well logs, well elevations, quantity pumped, power usage, surface inflows and outflows, stream accretion and depletion data, analyses of water quality, geologic data from which the underground formations can be reconstructed, records of drainage and other discharge, and meteorological records.

Records descriptive of the economy of the basin should also be available. These include the type and extent of irrigated or dry-farmed crop; records of soil moisture and crop evapotranspiration; urban and domestic water supplies, requirements, and use; and historical records of development as it occurred in time and extent. It will seldom occur that all information and data will be available in usable form, nor are the data mentioned in the preceding text exclusive of all other pertinent information.

The listing does, however, present an indication of the scope of desirable coverage of data.

An investigation of ground water conditions in a partially developed basin often occurs following a period of declining water levels in the area. There is a tendency for human nature, particularly during drought periods, to regard any drop in the ground water elevation as an indication of danger, without consideration of the fact that supply to the water table at such times is below average. The drop may, in many instances, actually be of measurable benefit in salvaging uneconomic consumptive use or outflow and in providing underground storage for supplies available during an ensuing wet cycle. Many users of ground water feel that the ideal situation involves keeping the underground reservoir as full as possible and large expenditures frequently have been made for this purpose. The result has usually been a slight saving in pumping costs, accompanied by tremendous waste of surface supplies in years of normal or above-normal runoff.

The disposal of water from an underground basin must, over a long period of time, be equal to the recharge. Under virgin conditions, previously discussed, disposal is effected through natural processes by evapotranspiration from high water table lands, surface outflow through effluent streams, and subsurface outflow. Development and utilization of ground water results in salvage of all or a portion of the natural disposal, which in turn creates empty underground storage capacity and opportunity for additional replenishment. The criteria usually applied to determine the usable annual draft from a ground water basin are:

1. The annual net draft over a long period of time must not exceed the average annual replenishment.

2. The net draft must not lower the water table (or pressure surface), in a series of dry years, to the point where economic pumping lifts are exceeded.

3. The net draft must not be so great that, over a long period of time, deterioration in quality to the point of the supply becoming unusable would occur.

The "safe" or operational yield would then be represented by the quantity which may be withdrawn annually without inducing undesirable conditions. Draft in excess of this quantity is generally termed overdraft. If the first of the above criteria is applied to a given situation then, during a period in which the supply is essentially equal to the long-time mean supply, the decrease in the quantity of storage (represented by, under water table conditions, the difference in water level multiplied by the specific yield of the dewatered deposits) is equal to the total overdraft for the period; and the difference between present annual draft and average annual draft during the mean period, added to the average annual decrease in storage, is the present annual overdraft.

The determination of the sustained operational yield and overdraft, if any, from a ground water basin requires evaluation of the items forming the so-called equation of hydrologic equilibrium, which is: surface inflow plus precipitation on surface plus subsurface inflow plus imported water (if any) equals surface outflow plus subsurface outflow plus evapotranspiration plus exported water (if any) plus or minus the change in ground water storage.

A drop in water levels does not, by itself, indicate overdraft. Use of either a surface or an underground reservoir implies withdrawing water and lowering, at least temporarily, the level attained by the water in storage. In a dry year, or a dry period, natural recharge is less and the demand generally greater; these factors combine to accentuate the recession in water levels. The most important factor in the evaluation of long-time operational yield and determination of overdraft is whether the storage capacity available is sufficient to supply the demand over a series of dry years and recover to former levels during the ensuing wet period.

The change in underground storage includes not only the change occurring beneath the water table (surface of the saturated zone of sediments) but also that within the root zone, and that between the root zone and the water table, for the period of time considered. All of the elements of supply and disposal, with the possible exception of precipitation are, or can be, affected to some extent by the activities of man. Recent experimentation and research on cloud-seeding may even bring precipitation within the control of man within the next few years.

An accurate evaluation of change in underground storage must be predicated upon a reliable delimitation between zones of free (unconfined) and of confined ground water. It must also be realized that even in areas underlain by confined ground water, an unconfined ground water body will usually exist in the sediments comprising the formations between the confining layer (causing the pressure to exist) and the surface of the ground. A drop in water levels in a pressure area indicates a recession in the piezometric surface or pressure relief, and is not a measure of decrement in underground storage. The water-bearing formations in a pressure area remain saturated until the pressure level drops below the bottom of the impervious stratum overlying the aquifer. With the exception of water deriving from possible subsidence of the area, actual dewatering occurs in adjacent unconfined ground water bodies that act as forebays to the pressure area. Accurate delineation of pressure areas is of sufficient importance to warrant a detailed geologic study. This will constitute an independent check on the hydrologic determination through observations of ground water behavior under static, heavy draft, recharge, and discharge conditions. The governing factor in the operating yield of an aquifer in a pressure area is the transmission capacity of the aquifer, whereas for water table conditions the controlling factors are the underground storage capacity and the rate and amount of recharge.

The total of the following items, corrected for any change in storage above the water table, would represent the aggregate supply to ground water storage:

Percolation from precipitation
Percolation from stream channels, lakes, pools, and reservoirs
Artificial recharge through spreading areas, "inverted" wells, etc.
Underflow to the basin
Percolation from applied irrigation water
Seepage from cesspools and septic tanks
Leakage from water mains, sewerage systems, and storm drains

In many existing ground water basins, the opportunity for recharge from stream bed percolation is limited due to the presence of high water tables in the area traversed by the channels.

All of the items in the foregoing list are affected by the development and culture constituting the economy of the overlying lands. To illustrate, in a state of nature average percolation from precipitation is generally minor in amount, as the type and density of natural vegetation that becomes established is usually such as to use practically all of the available average annual rainfall. With the substitution of an irrigated culture for native vegetation, percolation of precipitation tends to increase, as the initial soil moisture deficiency at the commencement of the rainy season is generally less. Regulation of runoff may increase stream bed percolation and allow greater opportunity for artificial recharge operations. Regulation of flow from a portion of the watershed allows a greater portion of the flow from the unregulated area to percolate naturally, or be spread. Stream bed percolation, on the other hand, may be diminished or practically halted by installing essentially impermeable linings in conveyance channels.

If the storage capacity of the ground water basin is comparatively large it may be drawn down to a considerable extent without danger or deficiency. Should complete recharge be accomplished during wet periods, from natural percolation, there is little benefit to be gained from artificial recharge other than the accomplishment of refilling the basin at an accelerated rate. Very little overall conservation of water would be attained thereby. It should be remembered that where artificial recharge projects are in operation, the actual benefit gained is equal to the difference between the quantity spread and that which would, in any event, have percolated through natural processes.

Water reaching the water table is disposed of by pumped extractions, subsurface outflow and effluent seepage (rising water), consumptive use by vegetation deriving the required water supply directly from the water table, and induced drainage.

The elevation of the water table affects the magnitude of subsurface outflow, effluent seepage, drainage, and evapotranspiration of vegetation. In cases where underflow, drainage, and effluent seepage constitute a source of supply to lower basins, no net advantage (on a broad, or regional basis) will be gained by decreasing the magnitude of these items through lowering the water table in any one basin. However, where phreatophyte growth occurs, feeding directly on the water table, considerable salvage of usable water supplies can be accomplished by such lowering. Some ground water must be allowed to escape from the basin in order to prevent a gradual build-up of dissolved salts to harmful concentrations.

The salt balance condition in a ground water reservoir is of prime importance in the determination of operating criteria and yield. In general, less than one-half of the applied irrigation water is retained within the root zone and is available for evapotranspiration uses. The remainder, in free ground water basins, either drains off on the surface or percolates downward to the ground water body. In pressure areas, the percolate will form a perched ground water body, often consumed by evapotranspiration of native vegetation in swamp areas unless adequate drainage has been provided.

If the output of ground water exceeds the input, and if there is little or no subsurface outflow or effluent seepage, mineral solubles will be retained in the ground water basin. The unconsumed portion of applied irrigation water in free ground water areas will circulate between the surface and the water table and on each trip will carry an additional load of mineral solubles to the main ground water body. The water in storage will gradually deteriorate in quality, becoming unusable in the course of time, unless adequate drainage is provided. The effluent salts in surface and subsurface outflow plus any exported water or sewage should be equal or greather than the quantity entering the basin in order to stabilize the quality of the retained water and achieve a favorable salt balance.

Disposal from the water table must equal the supply, plus or minus the change in storage. If the net change in storage over a complete cycle, encompassing wet and dry periods, is negative, then the basin is overdrawn with respect to the historic conditions of water supply and natural recharge. It is apparent from the preceding discussion that the "safe" yield is neither a unique, nor a fixed, value. It is also obvious that the water table must be lowered somewhat below that existing under natural conditions in order that there may be an operating yield. The yield represents, in part, salvage from natural processes of disposal by subsurface outflow, effluent seepage, and vegetative consumptive use and, in this respect, can be achieved only by a lowering of the water table. A lowering of the water table may also induce increased stream bed percolation and provide more space for the storage of surplus water in wet years. The quantity of operating yield is dependent, other factors remaining the same, upon the assumption as to the average elevation at which the water table is to be stabilized. With extractions limited to operating yield, the water table will fluctuate around this average, more or less in accordance with the sequence of wet and dry years. The yield obtainable will change in magnitude as man's activities and developments alter either the water supply available for ground water storage or the disposal of ground water in storage.

Exploitation of ground water resources has often been uncontrolled, without the benefit of intelligent planning. In the semi-arid regions of the western United

States, for example, the ground water operating yield will generally be exceeded prior to full development of the basin. If overdraft conditions prevail for an unreasonably long period (which must be individually determined for each specific basin) destruction of the utility of ground water resources will be threatened through progressive lowering of water levels and deterioration in ground water quality. The evaluation and physical solution of a ground water problem includes determination of the following listed factors:

1. Where additional water is needed
2. How much supplemental water is presently, and will ultimately be, required
3. The location of sources of good quality water
4. Feasible methods for the capture and storage of surplus waters
5. The distribution of required water supplies
6. Economics and financing of supplemental water supplies

The solution to ground water problems generally involves continued utilization of the natural storage capacity in the ground water basins in conjunction with increased direct diversion supplemented by surface storage. It is, of course, necessary to maintain hydrologic balance between water supply and disposal under any plan of water conservation and utilization. If supplemental water in excess of overdraft is brought to, and distributed in, a ground water basin, unnecessary waste, often accompanied by damage from waterlogging, frequently results. Disposal facilities will be required, either in the form of additional draft on, and use of, ground water or by development of a comprehensive drainage system. Proper planning and constant supervision usually pays appreciable dividends in the form of operating economies.

4. The Fully Developed Basin

For the purposes of this paper, the fully developed basin is defined to be one in which the utilization of water is much greater than the natural operating yield. Consequently, additional water supplies must be made available for use. This will often entail, not only surface storage and delivery, but the operation of extensive works for the artificial recharge of the ground water storage capacity of the basin and close and continuous supervision of ground water extraction and drainage operations. It is absolutely essential that accurate, detailed records of all aspects of water supply, movement, use, and disposal be kept for control purposes. This section will discuss some of the operational problems encountered in the complete utilization of both ground and surface water resources, with particular reference to the ground water aspects.

The maximum utilization of available storage facilities, both surface and underground, can be achieved through the planned coordinate operation of such storage capacity. This will usually entail the operation of surface reservoirs on an annual yield basis, with cyclic regulation of temporary surpluses being provided by underground storage. Conjunctive operation of surface and underground storage reservoirs can be accomplished only after thorough investigation and research with respect to all pertinent elements in a specific locality.

A comprehensive plan for the management and control of water resources should provide for continuity of engineering investigation and the development of adequate hydrologic, geologic, and geographic data; the creation of appropriate agencies for management of the coordinated operations; and for the financial base to support management programs. In many instances, these requirements cannot be provided in limited areas or under private auspices. The areas and functions to be covered are generally so extensive and affect such a broad sector of public interest that they appear to be feasible of accomplishment only through official agencies.

The hydrologic and operational problems encountered in utilizing underground storage capacity are almost inseparable as such due to the nature and extent of the usual ground water reservoir. In many cases, such as in the western United States, the underground reservoir is far larger in surface area and in total storage capacity than available surface reservoir sites.

Natural annual recharge, however, is usually much less, in proportion to storage capacity, than the annual supply to surface reservoirs. Ground water reservoirs may, in years of deficient surface supplies, be drawn down to the greatest practicable extent, whereas surface storage, because of lesser capacity, has a definite limited annual ability to yield a water supply for beneficial use. Ground water reservoirs serve frequently as regulators of stream flow, maintaining such flow over periods of deficient precipitation. In the operation of underground storage, the average annual discharge may exceed the annual recharge for much longer periods than is possible with surface reservoirs, if the long-time average annual recharge and discharge are maintained in hydrologic equality.

Ground water storage is generally affected by overlying land use only to the extent that the rate of downward percolation from the soil has been modified. Since only water that is surplus to the needs of the soil percolates downward to the ground water body, quantities are governed not only by the amount of infiltration, but also by the evaporation and transpiration occurring at the surface. Comparative evapotranspiration before and after change of land use is an important factor in determining the effect of land use change upon storage in ground water reservoirs.

The reduction of overland flow by effective land management generally increases the vertical movement of water into the soil. Many of the methods and practices followed in soil conservation projects are utilized in the artificial replenishment of ground water reservoirs, although the objective of these latter procedures is the increased conservation of available water supplies. Thorough geological investigation is required for delineation of the recharge areas of most ground water reservoirs, as it is necessary to establish that the available surplus water is being applied in the intake area of the underground reservoir. A parallel requirement is that the water applied for artificial recharge reaches the main ground water body of the reservoir and is not dissipated by excessive evapotranspiration from the root zone of vegetation, or in high water table areas. The success of water-spreading projects is principally dependent upon the rate of infiltration that can be maintained in the intake area. Difficulties have been encountered due to chemical constituents and sediments carried by flood waters, which may tend to seal the pores in the upper soil layers.

The problem of disposal of precipitation is intimately related to that of management of the ground water reservoir. Overland runoff can dissipate the upper soil layers, erode fields by gullying, and create problems of silt control for downstream users of water. Water which infiltrates into the ground, however, may remain in the soil layer for subsequent use by growing crops. Soils and rock materials forming the land surface vary widely in their capability for absorbing, storing, and transporting water. By far the greater part of the land surface is formed by materials slightly to moderately permeable. The surficial materials in some areas are exceedingly permeable and overland runoff rarely occurs, while on other areas negligible infiltration takes place due to impervious upper soil layers. The works of man, including drainage projects, housing, and road and airfield surfacing, have had a decided adverse effect on the infiltration of precipitation.

Many problems resulting from development of ground water storage are occasioned by inability of the reservoir to provide the amount of water needed at the time and place required. Problems due to the inadequacy of the ground water storage capacity to meet the demands made upon it are concerned with total availability of water supplies and if the reservoir is not naturally replenished in sufficient quantity to satisfy the demand, the problem is one of real shortage of water. Other problems may develop in an underground reservoir due to physical limitations, or to the ability of the water to move through the aquifer at a rate sufficient to meet the withdrawal requirements at specific locations. Problems of loss by wastage or leakage, and subsurface outflow, uneconomic consumptive use, or of contamination of the supply by dilution with saline or poor quality water, are typical of the hydrologic considerations requiring solution.

Increments to storage also affect the position of the water table in the recharge area. Therefore, coordinated analyses of records of infiltration, soil moisture, storage and discharge, stream seepage, and ground water storage in the recharge area are needed for a thorough determination of ground water recharge. Similarly, determinations of natural discharge from the ground water reservoir require adequate data as to evapotranspiration, outflow in springs and seepage to streams, loss of storage by subsurface outflow and changes in the volume of water in storage.

Pumping from a well, or closely spaced group of wells, creates a cone of depression in the water table or pressure surface of an aquifer. Generally, if withdrawal of water constinues at a constant rate, the cone expands and the pumped water draws water from a progressively increasing area. The water level in the well continues to drop, but at a decreasing rate, until the cone has expanded to reach either an area of natural recharge or discharge. At such times as the amount withdrawn is balanced by increased movement from the recharge area or decreased natural discharge, the progressive lowering of the water table will cease due to stabilization of rates.

The solution to problems of apparent or local shortages of water is to effect a balance between the rate of draft and the rate of replenishment, either by reducing the draft or increasing the replenishment, or both. The principle is the same as that involved in the elimination of overdraft from reservoirs where long accumulated storage is being progressively depleted. Other corrective measures that are effective in many areas include development of wells in previously untapped portions of the aquifer or redistribution of wells to draw from a more extensive part of the aquifer.

Pumping from wells increases the rate of ground water movement from the recharge area to the pumping area by increasing the hydraulic gradient. In many areas the water levels in wells reach approximate equilibrium after years of pumping, an indication that the pumped water is now replaced by inflow of water through the aquifer. Such balance cannot feasibly be obtained, however, where it requires pumping lifts so great as to be economically prohibitive or where the aquifer would be unwatered in the process of establishing a favorable hydraulic gradient. In areas where pumping has created conditions favorable to subsurface inflow of poor quality water, further pumping will serve only to aggravate the problem. Remedial measures for salt water encroachment require either reduction of pumping draft or the artificial replenishment of the aquifer where the storage is being depleted.

A further operating problem arises in maintaining the water table at an elevation below the root zone of overlying vegetation, and below the limits of capillary action, in order to the reduce loss of storage due to excessive evapotranspiration. Other losses, principally those due to waterloving vegetation and subsurface outflow from the basin, will occur but these are also subject to a measure of control. Subsurface outflow is usually dependent upon the elevation of the water table at a point some distance upstream, or upbasin, from the point of outflow, and such water may in large measure be salvaged for use as a part of the annual supply through a program of pumping from that part of the reservoir closest to the subsurface outlet.

Special operating problems will be evidenced in some basins due to local geographic and geologic factors. The prevention of sea-water intrusion is a continuing problem in coastal ground water basins, many of which have been drawn down to such an extent that sea water has presently penetrated into the aquifers with deleterious effect on the usability of the remaining supply. Experiments in the prevention of such intrusion by the operation of a line of coastal injection wells have been made during the past few years by the State of California and the Los Angeles County Flood Control District, and a research project covering the same general problem has recently been completed by the University of California.

The quality of ground water is of concern to all users, but particularly to agriculture and industry. An understanding of variations in the quality of water in various parts of the ground water reservoir requires also a knowledge of the geology and of movements of water in the reservoir.

Numerous examples exist of local contamination of ground water by the disposal of wastes. In some cases, such contamination has forced abandonment of producing wells. Should artificial recharge of underground reservoirs become general, such contamination is likely to become a serious problem unless adequate precautions are taken to prevent recharge by contaminated water. Industrial wastes are the major source of soluble nonputrescible wastes. Sewage may also carry significant quantities of soluble inorganic material. Numerous instances exist of contamination of ground water by discharge of waste into pits or ponds from which subsequent percolation of such waters has occurred. When these wastes penetrate ground water reservoirs, dilution occurs slowly and the effects of such contamination are long lasting.

The rivers draining the principal stream basins have become, in effect, sewers draining their areas, and it appears inevitable that one of the future major functions of valley surface streams will be the disposal of wastes from living processes, as well as from industrial processes. The waste loading may render the stream water unusable for other uses unless sufficient dilution occurs, and it is frequently required that certain wastes be treated prior to discharge into streams, or be otherwise disposed of. Many potentially harmful types of pollution can be successfully treated prior to discharge into surface water courses.

Ground water which has been contaminated by infiltration from polluted streams creates a serious problem. Surface streams can be controlled by corrective action at the source of pollution, but a contaminated body of ground water may well require several decades for successful treatment. Wherever wells pump water which is replenished by river infiltration, the ground water body will eventually be contaminated by soluble chemical wastes carried in the stream, unless proper control of surface contamination is exercised.

Another form of progressive deterioration in quality of water may occur in reservoirs that are replenished in large part from water that has already been subjected to use and has absorbed soluble contaminating material. Pumping from such reservoirs is a contributing factor to such deterioration to the extent that the available storage is emptied sufficiently to induce replenishment by contaminating waters. The basic cause of such contamination is the development and use of the water before it reaches the ground water reservoir in question. The problem of increase in salinity is not solved by limiting the application of irrigation water to the required consumptive use, even if practical means could be developed to provide only such quantities of water as are required by growing crops. Since most water applied to irrigated crops carries some mineral matter, these salts will accumulate in the soil even if all applied water is beneficially consumed in promoting growth. Effective irrigation practices include the removal of salt residues from the soil by the application of water in excess of the consumptive requirements of the plants and the consequent leaching of the upper soil layers.

The subsurface inflow of water of poor quality is generally a more serious problem. It may necessitate the abandonment of wells owing to dissolved impurities that may render the pumped water unfit for general use. Another specialized problem has developed due to the use of surface water for irrigation. In some areas this has been accompanied by a rise of the water table due to percolation from the irrigated areas. Under natural conditions ground water is at shallow depths in the low central portions of most larger valleys and near the channels of flowing streams. In valleys where irrigation development by surface water diversion has occurred, the water table has risen under many of these lowland areas due to lateral movement of ground water from higher irrigated lands. Drainage is necessary to accomplish reclamation of such high water table lands.

Where eroded gullies have been cut deeply enough to intersect the water table, drainage has often been accomplished as effectively as it would have been by a drainage canal of similar depth. However, in the usual case, it will be necessary to construct and operate planned drainage facilities in order to maintain the water table at the desired depth. These facilities may consist of wells, open ditches and canals, or subsurface tile or gravel drains. Means for the disposal of the drainage water must also be provided.

This summary of operating problems encountered in the management of ground water basins has, of necessity, been devoted to highlighting factors usually considered to be of some importance. A more thorough treatment of such problems, and other important aspects of ground water operations, will generally be found in the many excellent texts providing ample coverage of the field.

LES RELATIONS ENTRE LES EAUX SUPERFICIELLES ET LES EAUX SOUTERRAINES

J. TIXERONT(*), M. CHAUMONT (**) et H. ZEBIDI (***)

Dans les régions arides, toutes les ressources d'eau doivent être utilisées : eaux souterraines et eaux superficielles, car les besoins dépassent le total des ressources. Il faut donc en coordonner l'emploi.

La note actuelle présente des observations sur ce sujet, limitée à trois points :

1. Ecoulement total d'un bassin en présence ou en l'absence de nappes souterraines.
2. Part du ruissellement dans l'alimentation des nappes souterraines.
3. Exploitation coordonnée des deux catégories de ressources.

1. L'ECOULEMENT GLOBAL EN PRESENCE OU EN L'ABSENCE DE NAPPES SOUTERRAINES

Les postes hydrométriques du Réseau Tunisien sont situés à l'aval de bassins étendus, et constitués en général de façon prédominante par des formations imperméables sous-jacentes à des sols normalement développés. La pluviométrie des bassins contrôlés varie de 300 à 1500 m/m. Le ruissellement constitue la partie essentielle de l'écoulement.

L'ensemble des observations peut se traduire par la formule suivante qui relie l'écoulement (R) à la pluie (P) et à l'évapotranspiration potentielle, E (2) : ces termes étant exprimés en unité de hauteur d'eau.

$$R = \sqrt[n]{P^n + E^n} - E \quad \text{(a)}$$

Cette formule est approximativement vérifiée en Tunisie pour $n = 3$.

L'évapotranspiration potentielle de Thornthwaite varie de 0,75 m à 1,20 m. Pour des bassins s'écartant des conditions habituelles, la formule (a) n'est plus vérifiée. C'est le cas en particulier pour les bassins très perméables, pour les bassins à sols squelettiques et pour les bassins réunissant ces deux caractéristiques, tels que les massifs calcaires.

Pour de tels bassins, nous pouvons comparer le résultat de l'application de la formule (a) avec l'écoulement réel qui totalise l'écoulement superficiel et l'écoulement souterrain. Cette comparaison est donnée par le tableau 1.

E_r est l'évapotranspiration potentielle de la station de référence (8), calculée suivant la méthode de Thornthwaite.

E est l'évapotranspiration potentielle obtenue pour le bassin en faisant subir à E_r une correction du gradient altimétrique déterminée grossièrement par interpolation entre les postes les plus voisins.

P_r est la hauteur de pluie à la station de référence.

P est la hauteur de pluie admise en faisant subir à P_r une correction grossière résultant de la carte pluviométrique de la Tunisie.

R_a est l'écoulement calculé par la formule (a)

R est l'écoulement observé.

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TABLEAU 1

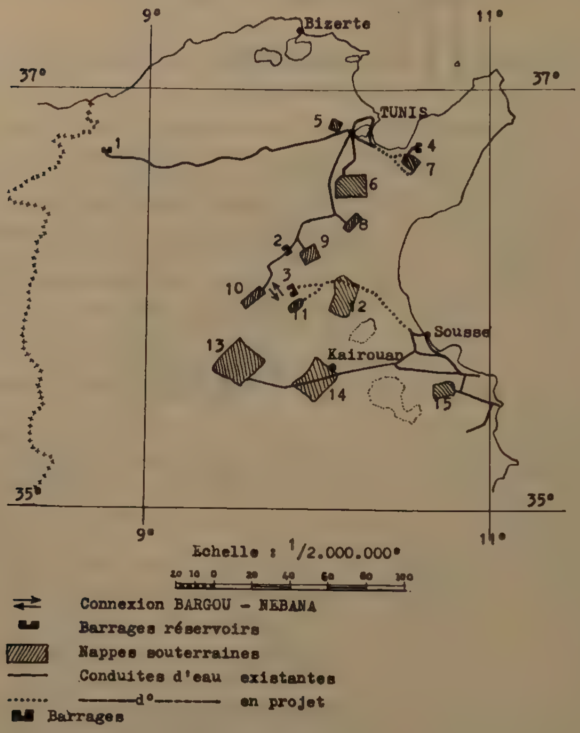
Ecoulement de Bassins plus ou moins perméables

Nº	Bassin	Evapotranspira-tionpotentielle			PLUIE			Ecoulement			
	Désignation	Station de Référence	E_R	E	Station de Référence	P_r	$P.$	R_a	R	R_{ab}	Référence bibliographique
1	Djebel Chenata	Bizerte	928	900	Bouzaria	633	700	114	264	255	13
2	Ben Saîdane	Zaghouan	938	870	Djougar	472	560	80	108	150	13
3	Zagouhan	Zaghouan	938	830	Zaghouan	463	650	116	166	217	13
4	Oued Kasseb	A. Draham	795	870	Diverses		1187	456	512	522	4
5	Oued Ellil	A. Draham	795	850	A. Draham	1650	1290	553	574		6
6	Oued Zerga	Tabarka	922	900			1314	540	420		3
7	Oued Maden	Tabarka	922	900			840	211	310	271	3
8	Ouchtata	Tabarka	922	900			1000	300	480	480	3
9	A. Bou Rass.	Bizerte	928	900			700	114	220	255	10

1 - 2 - 3 : Massifs calcaires Karstiques.
4 - 7 - : Bassins comportant environ 40% de calcaires très perméables.
5 : Bassin imperméable contigu de 4.
6 : Bassin imperméable voisin de 7 et 8.
8 - 9 : Massifs de dunes de sable.

TUNISIE

Interconnexions région de Tunis et Sahel



LÉGENDE

Barrages
1 — Oued El Lil
2 — Oued Kébir
3 — Oued Nébana
4 — Oued Bézirk

Nappes souterraines
5 — Manouba
6 — Khlédia
7 — Soliman Menzel bou Zelfa
8 — Zaghouan
9 — Bent Saïdane
10 — Bargou et Kébir
11 — Bou Moura
12 — Sisseb
13 — Bou Hafna
14 — Kairouan
15 — Beni Hassen

Le tableau donne la publication de référence.

A titre de comparaison, on a porté au tableau les mêmes éléments pour l'Oued Ellil, et l'Oued Zerga, bassins à peu près imperméables situés au voisinage des bassins de l'Oued Kasseb et de l'Oued Maden. Le bassin de l'Oued Ellil a une assez bonne couverture forestière. Celui de l'Oued Zerga a une excellente couverture forestière.

On rapprochera ces résultats de ceux obtenus pour les montagnes calcaires d'Israël (7), où l'écoulement souterrain représente 95% du total.

La valeur de l'écoulement souterrain correspond approximativement d'après Goldschmidt à :

$$ES = K(P - 360)\ \mathrm{m/m} \tag{b}$$

Le coefficient K varie entre 0,70 et 0,90. Nous admettrons une valeur de 0,75.

Pour une pluviométrie de 800 m/m, on aurait un écoulement souterain de 340 m/m, alors que la formule (a), avec une évapotranspiration potentielle de 800 m/m donnerait un écoulement de 210 m/m.

Si pour les bassins Tunisiens du tableau 1, on applique la formule (b) aux zones perméables et la formule (a) aux zones imperméables, on obtient les valeurs figurant à la colonne R_{ab} du tableau. Il y a quelque chance que R soit un peu sous évalué dans les bassins n° 2, 3, 8 par l'enregistrement insuffisant des plus forts débits d'écoulement. Il faut savoir d'autre part que la capacité de rétention superficielle du bassin n° 1 est nettement plus faible que celle des bassins nos 2 et 3.

Vu l'imprécision des éléments de comparaison, on ne peut pas tirer à ce stade des conclusions quantitatives de cet examen. On peut cependant en tirer quelques remarques.

1. L'écoulement global des bassins est augmenté par la présence de formations perméables. Il est au contraire diminué par la présence d'une excellente couverture forestière (bassin 6).

2. On se propose parfois de rechercher des formules synthétiques donnant les écoulements moyens en fonction du climat moyen. Dans le cas des bassins ordinaires où domine le substratum imperméable, une première approximation est donnée par des relations linéaires entre pluie et ruissellement. En deuxième approximation, en introduisant un terme d'évaporation on aboutit à la formule (a). La formule (b) est aussi du type linéaire en fonction de la pluie seule. Elle gagnerait sans doute à être complétée par un terme d'évaporation, et un terme caractérisant la rétention superficielle.

3. Pour les bassins à écoulement souterrain, en effet, le problème se complique par suite de la grande différence entre les caractères des affleurements alimentaires, en ce qui concerne la rétention superficielle et l'évapotranspiration potentielle. (Il ne s'agit plus ici d'E.T.P. climatologique, mais de la potentialité du climat associé au terrain). D'autre part, comme pour le ruissellement, les formules synthétiques ne valent que pour les moyennes et c'est un peu abusivement que nous avons introduit dans le tableau 1 les bassins 6 et 7 pour lesquels on n'a qu'un an d'observation. Nous l'avons fait à titre indicatif, et parce qu'il s'agit de bassins à forte pluviosité, la relation entre pluie et écoulement devenant plus étroite aux fortes tranches de pluie. Cependant, on ne peut se dispenser d'établir les bilans annuels en comptabilisant la pluie réelle. Cette méthode, que Berkaloff et l'un de nous avons appliquée aux bassins 1, 2 et 3 (13) est analogue à celle qui a été appliquée par Thornthwaite à des bassins ordinaires (14). Elle présente l'avantage de déterminer par observation et analyse les facteurs caractéristiques de l'écoulement dans les massifs calcaires : surface d'alimentation, évapotranspiration potentielle, hauteur de rétention superficielle. Elle peut même être améliorée en calculant un facteur de corrélation entre la pluie à une station de référence, et la pluie qui tombe sur les affleurements. En possession de ces éléments caractéristiques pour un certain nombre de formations connues, on arrivera à les prévoir pour des formations analogues, sans avoir besoin de longues durées d'observations, et on sera mieux armé pour la recherche des formules synthétiques.

4. Telles sont les voies que nous suivrons pour arriver à préciser l'influence des nappes souterraines sur l'écoulement global, et la répartition de cet écoulement entre le ruissellement et la percolation.

2. La part du ruissellement dans l'alimentation des nappes souterraines

Les nappes souterraines ne peuvent pas être alimentées avant que le sol, au-dessus des affleurements, atteigne un taux d'humidité minimum. Cela est vrai, même pour les massifs calcaires. Ce taux peut être dépassé sur une vaste étendue des affleurements lors des fortes pluies, ou bien, localement le long du lit des cours d'eau par la conceàtration du ruissellement.

Le premier processus tient le rôle principal dans les régions humides. L'un de nous a fait remarquer qu'on ne pouvait pas l'éliminer complètement, même dans les zones très arides (11). Essayons de préciser ce point. Nous nous baserons sur la statistique des pluies de trois jours consécutifs, délai assez court pour que l'évaporation n'ait pas le temps de reprendre beaucoup d'eau. Le tableau ci-dessous donne la période de récurrence des pluies de trois jours ayant dépassé 100 m/m, d'après les observations tunisiennes de 1901 à 1955 (1).

TABLEAU 2

Pluies de 3 jours ayant dépassé 100 m/m en Tunisie

Station	Hauteur de pluie moyenne m/m par an	Période de Récurrence des pluies de plus de 100 m/m en 3 jours/années	Nombre d'années d'observations	
Tabarka	1.023	2	54	(1) Affleurements de la nappe Saharienne du continental intercalaire. (2) Affleurements des nappes miocènes centre Sud Tunisien. (3) Affleurements de la nappe miocène Saharienne. (4) Nappe Saharienne du continental intercallaire. On a utilisé 12 années d'observations à Fort Saint et 12 années d'observations différentes à Ghadamès, station située à 30 km de Fort Saint.
Tunis	427	6	57	
Sousse	320	6	54	
Kairouan	282	7	54	
Matmata (1)	238	5	51	
Maknassy (2)	150	10	43	
Gafsa (2)	157	80	50	
Tataouine (1)	122	30	46	
Tozeur (3)	89	80	51	
Fort Saint (4)	31	80	24	

La durée des observations utilisée ne permet pas une évaluation précise de la période de récurrence des pluies de 200 m/m. Toutefois, une extrapolation par la loi de Galton Gibrat donnerait pour les postes intéressant les nappes Sahariennes l'ordre de grandeur suivant pour les périodes de récurrence :

Matmata	30 ans
Tatahouine	1000
Tozeur	1000
Fort Saint	400

Beaucoup plus fréquentes pour ces nappes sont les occasions d'alimentation par le ruissellement. Les coefficients de ruissellement peuvent être très élevés sur les sols dont le caractère squelettique est très accentué : Rodier et Roche (9) ont trouvé dans le massif de l'Ennedi, (hauteur de pluie annuelle de l'ordre de 150-200 m/m) sur formations gréseuses très squelettiques, des coefficients de ruissellement de l'ordre de 55% pour des pluies de l'ordre de 10 m/m par jour, ou supérieures, qui représenteraient dans la zone Saharienne de la Tunisie, environ 70% de la pluie annuelle.

En l'absence de mesures hydrométriques régulières on peut avoir une limite inférieure des coefficients de ruissellement par l'évaluation de la consommation d'eau des champs d'oliviers et céréales cultivés en cuvettes dans les biefs supérieurs des Oueds Sahariens par des méthodes traditionnelles éprouvées, évaluation basée sur les notions acquises en matière d'évapotranspiration potentielle. L'analyse au moyen des photographies aériennes d'un certain nombre de bassins, nous amène à penser que sur la Crête du Dahar à la limite occidentale de la nappe du continental intercalaire, et sur les montagnes marno-calcaires immédiatement au Nord du Chott Djerid, les coefficients de ruissellement peuvent atteindre un ordre de grandeur de 10% (12).

Cette méthode nous paraît donner une possibilité d'attaque de certains problèmes d'alimentation des nappes Sahariennes. Tout le ruissellement issu des montagnes s'infiltre en général rapidement en arrivant dans les plaines.

3. L'EXPLOITATION COORDONNEE DES RESSOURCES

On sait que l'agriculture n'est pas possible dans les régions arides, sans l'intervention des réserves d'eau. L'agriculture sèche a été précisément inventée dans les régions arides pour permettre en se servant des réserves du sol d'adapter le cycle des précipitations au cycle de consommation des plantes utiles. L'irrigation est un progrès supplémentaire qui a suivi de très près la découverte de l'agriculture sèche. Laissant de côté pour l'instant les irrigations par épandage de crue, c'est l'utilisation des nappes souterraines comme réserves qui a été pratiquée le plus tôt, parce qu'elle nécessite seulement le captage peu coûteux de l'eau accumulée dans les réservoirs naturels, et que cette eau est soustraite à l'évaporation.

A l'échelle de la Tunisie, le volume global des eaux de ruissellement est par contre plus grand que ce qu'on peut tirer des nappes souterraines, compte tenu de leur taux d'alimentation. Un barrage réservoir permet de disposer au moment voulu de débits instantanés très importants qui ne pourraient être obtenus avec les nappes souterraines que par une multiplication prohibitive des points de captage, et avec des dépenses de pompage élevées. Par contre, en raison de la variabilité du ruissellement, les barrages réservoirs de la zone aride doivent avoir une capacité beaucoup plus grande que l'apport annuel, et on est limité dans cette voie par l'évaporation.

D'où l'idée d'associer étroitement les ressources et de les valoriser l'une par l'autre.

Cette association a été souvent réalisée. Par exemple aux U.S.A., la déficience du Barrage d'Eléphant Butte était atténuée en 1955 par des prélèvements massifs dans les nappes souterraines du périmètre du Rio Grande. A Tunis, les déficiences du barrage de l'Oued Kébir à la suite des années de sécheresse ont été partiellement compensées dans le passé par des prélèvements massifs sur les nappes souterraines de la Dorsale Tunisienne et des environs de Tunis.

L'examen de ce problème sur un cas particulier mettra en lumière les conditions de l'association et les résultats qu'on peut en attendre.

Le cas particulier choisi est celui de l'alimentation en eau du Sahel.

Nous disposons du bassin de l'Oued Nebana où la pluie est d'environ 430 m/m par an. Le ruissellement annuel est en moyenne de 35 millions de m^3, mais, en 35 ans, il a varié de 5 à 210 millions de m^3. Nous nous proposons d'en tirer le maximum d'eau en admettant que un an sur dix le déficit sur le volume d'eau distribué, soit au maximum de 30%. On peut faire un barrage réservoir à réserve interannuelle :

Soit V_r le volume de la réserve de régularisation.
V_S le volume nécessaire pour la sédimentation.
V_R le volume de la réserve totale.
VUA le volume annuel utilisable.

Le tableau ci-dessous donne VUA en fonction de V_r, en millions de mètres cubes par an (^{5}).

TABLEAU 3

Régularisation des eaux superficielles de l'Oued Nebana

Solutions	V_r	V_S	V_R	VUA
1	8	15	23	7
2	60	25	85	20
3	200	30	230	28

La première solution correspond à une trop faible utilisation. La troisième est d'un coût prohibitif. La deuxième est d'un rendement économique encore faible.

Nous disposons sur le parcours des conduites d'une nappe souterraine, dont les réserves sont d'environ 100 millions de m^3 pour une tranche de nappe de 10 mètres sous le niveau statique, et son alimentation annuelle est de 10 millions de m^3 (^{3}).

Si nous l'exploitons, nous pourrons non seulement utiliser en supplément les 10 millions de m^3 de la nappe souterraine, mais nous pourrons l'exploiter à débit annuel variable, en associant son exploitation à celle du barrage. Nous pourrions, par exemple, l'équiper avec un système de captages permettant de puiser au cours d'une année exceptionnelle 30 millions de m^3. Dans ce cas, nous pourrions, sans modifier la réserve totale de la solution 2, arriver à tirer du barrage les 28 millions de m^3 de la solution 3.

Mais ceci sera obtenu au prix d'un suréquipement de système de captages, qui sera peu utilisé la plupart du temps, au prix également de très fortes dépenses de pompage. Pratiquement, on a choisi d'équiper la nappe avec un système de captages permettant de prélever 20 millions de m^3 au cours des années où le ruissellement est déficitaire, et cela permet de compter sur un volume annuel utilisable de 24 millions de m^3, au barrage de l'Oued Nebana.

Dans cet exemple, nous avons été limités par les inconvénients d'un suréquipement qui ne sera utilisé que rarement. D'autres cas se présentent sous un jour plus favorable. Les dépenses de suréquipement diminuent beaucoup si on peut interconnecter une assez grande masse de ressources assez différentes pour diminuer la variabilité.

Pour l'alimentation en eau de Tunis par exemple, dans la période antérieure à 1929, l'alimentation se faisait par des sources dont les étiages pouvaient tomber à 6000 m^3 par jour. Un barrage fut construit sur l'Oued Kebir dont le ruissellement moyen annuel était de 10.000.000 de m^3 par an, et les conduites furent équipées pour l'adduction de 35.000 m^3 par jour. Or, ce bassin a une alimentation tout aussi irrégulière que le bassin de l'Oued Nébana, et le barrage se trouva vide au cours de plusieurs années au moment du maximum de consommation. Avant de passer au captage de nouvelles ressources d'eaux superficielles, on procéda à l'aménagement des nappes souterraines par l'installation de forages et stations de pompage sur les anciennes sources, et par la mise en exploitation de nouvelles nappes souterraines.

Les réserves des nappes souterraines intéressées dépassent largement celle d'eau de surface constituée par le barrage de l'Oued Kébir.

On put ainsi arriver en 1945 à prélever sur les nappes souterraines, un supplément d'eau atteignant en pompage maximum 35.000 m^3 par jour.

La variabilité de l'Oued Kébir se trouvait équilibrée, et il ne devint nécessaire de capter de nouvelles ressources qu'en raison de l'accroissement de la consommation. Ces ressources proviennent d'un barrage créé dans la Kroumirio où la variabilité d'alimentation est bien moindre, et où le régime pluviométrique est différent de celui du bassin de l'Oued Kébir.

En fait, le projet de l'Oued Nébana constituera même un début d'interconnexion entre le Sahel et la région tunisoise, en raison de la possibilité de transférer de l'eau entre les bassins de l'Oued Kébir et celui de l'Oued Nébana. On se reportera à ce sujet à la carte ci-jointe.

La coordination de l'exploitation des nappes souterraines et des ressources d'eaux superficielles est donc désirable et possible. Ces ressources sont valorisées l'une par l'autre, et leur association permettra seule, croyons-nous, d'arriver à un degré d'utilisation suffisant de l'ensemble des ressources hydrauliques.

RÈSUMÈ

Nous examinons quelques aspects des rapports entre les ressources d'eaux superficielles et les ressources d'eaux souterraines.

La présence de terrains perméables dans un bassin augmente le taux d'écoulement à pluie égale. Nous avons comparé à cet égard les résultats tunisiens et les résultats Israéliens. Nous pensons qu'on peut améliorer les prévisions concernant l'écoulement global et sa répartition entre les fractions superficielles et souterraines, en combinant les méthodes utilisées dans les deux pays et en faisant une place suffisante à la notion de l'évapotranspiration potentielle.

En ce qui concerne l'alimentation des nappes souterraines, nous avons essayé de préciser quelques indications déjà données, en utilisant quelques résultats récents sur le ruissellement en régions très arides.

En tout état de cause, pour arriver à l'utilisation maximum des ressources d'eaux, dans les régions arides, il faut associer étroitement l'exploitation des eaux superficielles et des eaux souterraines et compléter autant que possible cette association par de vastes interconnexions.

BIBLIOGRAPHIE

(1) B.I.R.H. (Bureau d'Inventaire des Ressources Hydrauliques de Tunisie) — Recueil des observations hydrométriques 1955-56 — Fascicule 4, Ecoulements et précipitations classés par fréquence.

(2) E. Berkaloff et J. Tixeront, Notice sur la Carte de Ruissellement annuel moyen en Tunisie. BIRH, Série I, Fascicule 7.

(3) A. Bonnier, M. Bouzid et O.W. Tscheltzoff, Note sur quelques méthodes d'estimation des ressources en eaux souterraines employées en Tunisie, *Présentée au Colloque d'Hydrologie d'Athènes 1961.*

(4) M. Chaumont, Hydrologie de l'Oued Kasseb, BIHR 1961(avec rectificatif concernant l'année 1953-1954).

(5) Cotha (Compagnie des Techniques Hydrauliques et Agricoles), Grenoble, Octobre 1957.

(6) A. De Montmarin, Etude hydrologique de l'Oued Ellil et de l'Oued Rhezala, Tunis 1952, Renseignements complétés par BIRH pour 1952 à 1960, sans modifier la relation établie pour la pluie avec la station de référence d'Aïn Draham.

(7) M.J. Goldschmidt, On the water balances of several Mountain underground, water catchments in Israel, Hydrological Service, H P 4, Jerusalem 1959.

(8) P. Preziosi, Le climat de la Tunisie, Evaporation, Bilans hydrologiques, zones climatiques, Journées de l'hydraulique à Alger, avril 1954, pages 81 à 88.

(9) M. Roche, Etude de l'écoulement en régime désertique, Massif de l'Ennedi, Campagnes 1957 et 1958, Orstom-Paris.

(10) A. Stebline, Renseignement verbal d'après les observations du Service des Eaux de Bizerte.

(11) J. Tixeront, Water ressources in Arid lands, in G.F. White, The future of Arids lands, A A A S, 1956, pages 101 et 102.

(12) J. Tixeront, La mise en valeur hydraulique du Sud Tunisien, BIHR, sous presse.

(13) J. Tixeront, E. Berkaloff, E. Mauduech, A. Caine, Bilan d'eau dans les massifs calcaires de Tunisie, AIHS, Bruxelles, 1951, Tome IV, pages 47 à 53.

(14) C.W. Thornthwaite and J.R. Mather, The water balance, centerton, New Jersey, 1955.

THE HUMBOLDT RIVER RESEARCH PROJECT, NEVADA

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ABSTRACT

The drainage basin of the Humboldt River, an area of about 16,200 square miles, ranges from a few to about 300 miles wide. The river flows westward from near the east boundary of Nevada to the Humboldt «Sink», a broad flat basin where the water is lost by evaporation. All of the water in the river previously estimated to be recoverable, including the flood flows, has been appropriated by users for many years. Development of the water resources of the Basin for the most efficient use is in a primary stage. Irrigation practices are not highly advanced except in a few scattered localities and in the distribution area of Rye Patch Reservoir, the only major constructed control on the river.

The long-range objective of the Research Project is to determine all water that may be made available for beneficial use in the Basin and to recommend efficient methods to accomplish optimum utilization of water resources. Secondary objectives include development of methods of evaluation and utilization and analysis of local developmental, scientific, and legal problems related to the overall water resources picture.

The chief amount of additional water that may be developed for beneficial use is that presently wasted by phreatophytes and other causes of evapotranspiration. In addition, water presently available for use may be more efficiently managed to increase the benefits from it. Development of additional water and more efficient management of present supplies may depend primarily on ways and means of withdrawing and recharging ground water.

Since it was not possible to study adequately the whole Basin at once, a reach of the River in the Winnemucca area, believed to be a well-defined hydrologic province, was selected in which to begin investigations. The primary aims in this initial phase of the Project include:

1. Development of methods and procedures for evaluating the magnitude of the components of the hydrologic cycle in a semi-arid basin.
2. Determination of geologic and geomorphic controls on water resources of the Basin, especially those related to movement, storage and availability of water.
3. Determination of consumptive use of water by crops, native useful vegetation, and non-beneficial vegetation.
4. Determination of the amount of water presently non-beneficially used by phreatophytes or otherwise being wasted that can be salvaged. Also devising and testing methods for the replacement of non-beneficial plants with beneficial ones.
5. Evaluation of the economics of modifying present farm practices or other water use in the Basin to increase the values of crops and products and thus the efficiency of water use.

To accomplish these complex aims two State agencies, two Universities, and six Federal agencies are cooperating on the Project. Progress on the work after two years of operation are reported in this paper.

RÉSUMÉ

Le bassin de drainage de la Humboldt River s'étend sur une surface d'environ 16.200 miles carrés avec une largeur allant de quelques miles à environ 300. La rivière s'écoule vers l'ouest depuis un point près de la frontière orientale du Névada jusqu'en Humboldt «Sink», un large bassin plat dans lequel l'eau se perd par évaporation. Toute l'eau de la rivière considerée comme récupérable, y compris l'écoulement

des crues, a été utilisée depuis de nombreuses années par les usagers. Le développement des ressources hydrologiques du bassin de façon efficace n'est qu'à son stade préliminaire. L'irrigation n'est pas très avancée sauf dans quelques localités dispersées et dans le domaine de distribution du «Rye Patch Reservoir», le seul ouvrage contrôlant la rivière.

Le but final du projet de recherche est la détermination de la quantité d'eau utilisable dans le bassin et la recommandation de méthodes efficaces pour l'utilisation optimum des ressources hydrologiques. En outre, l'eau utilisable actuellement pourrait être distribuée de façon plus efficace. Le développement de ressources supplémentaires et une meilleure utilisation de celles disponibles pourrait dépendre des méthodes utilisées pour l'exploitation et la recharge des eaux souterraines.

Comme il n'a pas été possible d'étudier de façon adéquate l'ensemble du bassin, un affluent de la rivière dans la région de Winnemucca, considéré comme une province hydrologique bien définie a été choisie comme endroit des premières recherches. Les buts principaux de cette phase initiale du project sont les suivants :

1. Développement des méthodes et procédés pour évaluer l'ampleur des composants du cycle hydrologique dans un bassin semi-aride.
2. Détermination des facteurs géologiques et géomorphologiques qui contrôlent les ressources hydrologiques du bassin, en particulier ceux liés au mouvement, accumulation et obtention de l'eau.
3. Détermination de la consommation en eau des récoltes et de la végétation locale utilisable ou non économiquement.
4. Détermination a la quantité d'eau qui n'est pas utilisée actuellement de façon rentable par les phréatophytes ou qui est perdue pour d'autres raisons et qui pourrait être récupérée. Choix et mise à l'essai de méthodes pour le remplacement de plantes non utilisables par d'autres économiquement utilisables.
5. Evaluation des conditions économiques qui seraient liées à une modification des méthodes actuelles de culture ou d'utilisation de l'eau du bassin de façon à augmenter la valeur des récoltes et par là l'efficacité de l'emploi de l'eau.

Pour accomplir ces buts complexes, deux agences d'État, deux universités et six agences fédérales coopèrent au projet. Les résultats obtenus après deux ans d'activité sont exposés dans le présent rapport.

1. INTRODUCTION

The amount of usable water severely limits the development and population of all arid regions in the world. At the same time overcrowding of humid regions is resulting in demand for more occupation of arid zones. Also, demands increase yearly for production of foodstuffs and other staples for which large parts of the arid zones are highly adaptable, apart from water shortage. Further, many semi-arid and arid regions are more pleasant and healthful places in which to live than presently highly populated areas.

The move toward aride zones is graphically illustrated in many parts of the world, for example, the colonization of North Africa by Europeans during the nineteenth and the early part of the twentieth century and migration to the Southwest United States from both the Eastern and the Pacific Coasts in the last thirty years. This population shift has resulted in development of acute or chronic water shortages and not infrequently in critical depletion of both surface and ground-water supplies. Some of the areas discussed in other parts of this symposium, especially the Central Valley of Arizona and parts of Tunisia, illustrate depletion of water supplies in arid zones.

Nevada communities have felt the pressures of growing population and developing agriculture and industry. Withdrawals of ground water in southern Nevada have exceeded perennial recharge for more than a decade. Only nearby Lake Mead and the convenient presence of a war-time built pipeline into Las Vegas Valley have allowed a rational and efficient basis for continued increasing use of water by the expanding population.

Northern Nevada has not been severely affected by such rapid population growth

but its imminence is readily discernable. In order to avoid overdevelopment and consequent depletion, and to utilize efficiently all available water, the Nevada Department of Conservation and Natural Resources has initiated a program to evaluate the water resources of the State. Any effort to attain this objective necessarily includes study of the Humboldt Basin, for more water is potentially available here than in any other basin in Nevada.

This paper describes the program and projects which have been initiated in order to gain knowledge of the hydrology and to develop methods of utilization of the water resources of the Humboldt Basin. Secondary objectives include development or discovery and application of scientific methods in arid-zone hydrology. In order to exemplify steps toward these objectives, general description of known facts pertinent to understanding hydrogeology and hydrology of the Basin is included. Work on the Project has been described in two progress reports published in 1960 and 1961 (Nevada State Department of Conservation and Natural Resources, 1960, 1961). Previous studies in the Basin include primarily ground-water investigations in Paradise, Reese River, and Lovelock Valleys and in the vicinity of Elko reported by Loeltz, Phoenix, and Robinson (1949); Waring (1918), Robinson and Fredericks (1946), and Fredericks and Loeltz (1951).

The Humboldt River Basin is about one-third of the area of northern Nevada, on the order of 16,200 square miles. The river flows about 260 miles from head to mouth and from the northeast to the southwest across the Basin. The headwaters are in the high Ruby Range and in somewhat lower country to the north on the north and east sides of the Basin. Most of the stream flow originates here and only small contributions of water flow into the channel farther downstream.

The crests of the higher ranges throughout the Basin are characterized by an alpine or sub-alpine climate; the mountain slopes and valleys in the headwaters regions between elevations of from 5,000 to 8,000 feet, by a semi-arid climate; and the lower areas from the latitude of Beowawe westward, by an arid climate. The pattern of the Humboldt River is that of a gaining stream flowing over relatively impermeable rocks from the uppermost headwaters to a point just below Palisade and of a losing stream, crossing areas floored alternately by permeable alluvial fill and less permeable bedrock, from Palisade to Humboldt "Sink". Within this pattern the stream gains and loses at several places west of Palisade as a result of variation in permeability of the bed and other factors, but these gains and losses are small compared to the overall loss by evapotranspiration.

Archeology, history, and legend attest that the Humboldt River valley has been a well-known oasis occupied by humans since prehistoric times. The Pre-Columbian Indians perennially occupied the valley. Explorers and trappers of European and American origin visited and described the river and environs early in the nineteenth century and, somewhat later, important way-stations were built along the river on the wagon trail to California. The valley was settled by miners and stockmen during the latter half of the nineteenth century. Construction of the transcontinental railroads stimulated settlement, exploitation of mineral resources, and use of water resources. Basically, the economy has remained unchanged since the turn of the century. Stock-raising and mining are still predominant industries.

Influx of settlers resulted in friction and litigation over use of water. During the thirties surface-water rights were adjudicated (Mashburn and Mathews, 1943) resulting in an effective, if perhaps temporary, settlement of such problems. At present all surface water and nearly all ground water are considered legally appropriated despite the fact that large quantities of water are wasted by evapotranspiration and smaller quantities flow into the barren wastes of the Humboldt "Sink".

The chief use of water in the Basin is irrigation, accomplished by flooding methods during the spring melt in the upper reaches and by more efficient methods in the

Lovelock area. Here, during the thirties, the Rye Patch Reservoir, the only major control structure in the Basin, was built by the U.S. Bureau of Reclamation to store water for irrigation purposes. Under present practices, two or more dry years in succession result in major losses of crops and resultant depressive effects on the economy. Major floods occur about once in ten years and periods of low flow occur two to three years out of ten, resulting in a "feast or famine" situation that restricts production and population growth to limits far below the potential that might be achieved by more efficient physical control, management, and use of water resources. The problems involved, then, center around (1) control and modulation of the river flow utilizing both ground and surface water in a pattern that will allow most efficient use without long-range depletion; (2) management of physical controls so that they support methods of utilization; and (3) economical utilization of water made available by the physical controls. This latter problem not only involves application of technical and scientific methods and tools but may require fundamental changes in the economy in order to financially justify construction of controls and employment of management.

2. THE NATURE OF THE PROJECT

Preliminary evaluation of these problems indicates that no single organization or agency in the United States possesses all of the facilities and, more important, the trained personnel to cope with the numerous and complex problems involved. Accordingly, the Director of the Nevada Department of Conservation and Natural Resources, with the advice of officials from several organizations, called upon the following agencies to handle the specific problems indicated (Nevada State Department of Conservation and Natural Resources 1960 and 1961):

1. Department of Conservation and Natural Resources, State of Nevada. General organization, administration, coordination and general support of the Project; support for supplementary weather stations and experimental plots, compilation and publishing of Project reports.
2. Bureau of Mines, State of Nevada. Geophysical work and some phases of the geologic work.
3. Departments of Geology, University of Nevada, University of Illinois. Most phases of the geology.
4. Desert Research Institute, University of Nevada. Some phases of hydrogeology and studies of evaporation.
5. U.S. Weather Bureau, Department of Commerce. Hydroclimatology.
6. Max C. Fleischman College of Agriculture, University of Nevada. Land and water use problems for agriculture.
7. Agricultural Research Service, U.S. Dept. of Agriculture. Some phases of evapotranspiration studies and chemical quality of water, land and water use.
8. Soil Conservation Service, U.S. Dept. of Agriculture. General mapping and aerial photography, mapping of phreatophytes, soil studies, land use problems.
9. U.S. Geological Survey, U.S. Dept. of the Interior. Collection, compilation, and analysis of basic hydrologic data, test-well drilling, some evapotranspiration studies.
10. Bureau of Land Management, U.S. Dept. of the Interior. Land tenure and land use problems.
11. Bureau of Reclamation, U.S. Dept. of the Interior. Support for evapotranspiration studies and assistance in planning for flood and other controls.

A detailed study of the whole Basin would not only result in expense beyond the foreseeable resources of State and cooperating Agencies but might also lead to duplication of work or to intensive studies in areas where they might not be needed

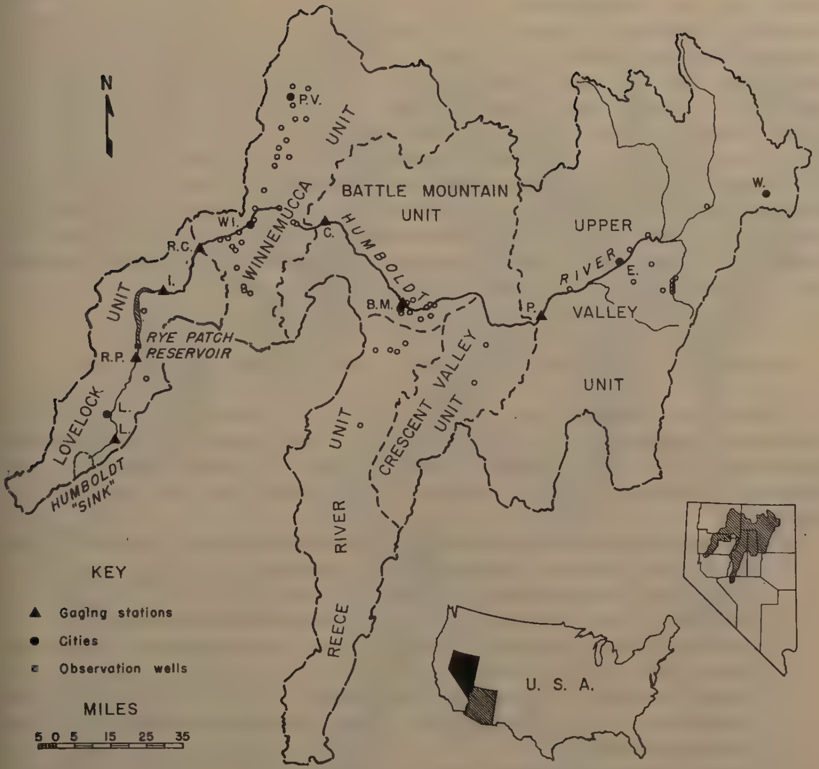

Fig. 1 — Hydrologic units, Humboldt Basin.

to attain desired results. Therefore it was decided to designate units of the Basin which would be more amenable to study and to select one unit for intensive investigation. It is believed that this procedure will result in development of methods and knowledge in early phases of the Project that will allow for more rapid, accurate, and perhaps less intensive study for remaining units. Accordingly, the following units, shown on Figure 1, have been designated, chiefly on the basis of hydrologic characteristics:

1. *The Upper Valley unit* extending from the uppermost headwaters of the Humboldt River to Palisade.
2. *The Battle Mountain unit* which extends from Palisade to the Preble Narrows near Comus.
3. *The Winnemucca unit* from Preble Narrows near Comus to Rose Creek and including the drainage basin of the Little Humboldt River and Grass Valley.
4. *The Lovelock unit* from Rose Creek to the Humboldt "Sink".
5. *The Reese River Valley unit.*
6. *The Carico Lake — Crescent Valley unit.*

The first four units include reaches of the Humboldt River whereas the last two are within the drainage basin but are not known to contribute surface water or significant quantities of ground water to the river (Waring, 1918, p. 110).

Considerable geologic and hydrologic study previous to development of this

Project had been accomplished in the Winnemucca unit. It indicated that local problems of substantial interest to the State Engineer and others might be solved by intensive study, problems that might not be solved unless they were studied in great detail. This plus other favorable factors including geographic location, size, variety of phenomena, and sympathetic interest of residents resulted in selection of the Winnemucca unit for the first phase of intensive study. Active field work in the unit was initiated in 1959 and will probably continue through 1963. Ultimately all units will be studied in more or less detail. Preliminary studies were initiated in the Battle Mountain Unit in 1960 and will continue in 1961. Meanwhile, a reconnaissance survey of the Humboldt River Basin under Section 6 of U.S. Public Law 566 allowing for the planning of control structures on small watersheds has been initiated and will undoubtedly result in making available useful data.

3. SUMMARY AND PRELIMINARY ANALYSIS OF WORK ACCOMPLISHED TO DATE

Although the Project is in its initial stages, study of various areas of work have resulted in knowledge that is of substantial value and interest. This information relates primarily to general features of the Basin and of the various units with some detailed data available for the Winnemucca unit. Briefly, the work accomplished includes:

1. Photography and topographic mapping of most of the Basin at suitable scale. Only a small part of the Basin remains unmapped.
2. Compilation of a generalized geologic map of the Basin.
3. Compilation and preliminary analysis of available hydroclimatic data.
4. Compilation and preliminary analysis of stream-flow measurements, water-well records, and other hydrologic data.
5. Detailed geologic and hydrologic field study is essentially completed in the Winnemucca unit, although some observations will continue for at least two field seasons.
6. Detailed evapotranspiration studies are progressing in this Unit. The Agricultural Research Service, the U.S. Geological Survey and Bureau of Reclamation, and the State Department of Conservation and Natural Resources have emplaced lysimeter tanks to study losses from native plants. In conjunction with lysimeter tanks, a weather station has been installed. The tanks have not been in place long enough to yield usable data.
7. The Soil Conservation Service has initiated surveys of areas of various phreatophytes. With this and the anticipated information from the lysimeters it is hoped that use of water by nonbeneficial plants can be determined. Studies will be conducted to discover and test useful vegetation to replace nonbeneficial phreatophytes.

The geologic work has resulted in compilation of a generalized geologic map of the Basin (fig. 2) which more or less effectively outlines lithologic controls on occurrence and movement of water. From this map it is evident that the surface lithology of the Upper Valley unit is essentially bedrock with only small areas of alluvium except in reaches of the southern tributaries, Pine and Huntington Creeks. Even in these valleys the alluvial deposits are thin and superficial except locally and, hydrogeologically, differ little from Tertiary sediments. Thus, the Upper Valley unit is characterized by highlands composed of intrusives, rocks of Paleozoic age, and volcanics and sediments of Tertiary age. The valley areas are floored primarily with Tertiary sediments and thin alluvium.

The highlands in the other units are essentially like those in the Upper Valley unit, differing primarily in containing less Tertiary sediments and intrusives. Also

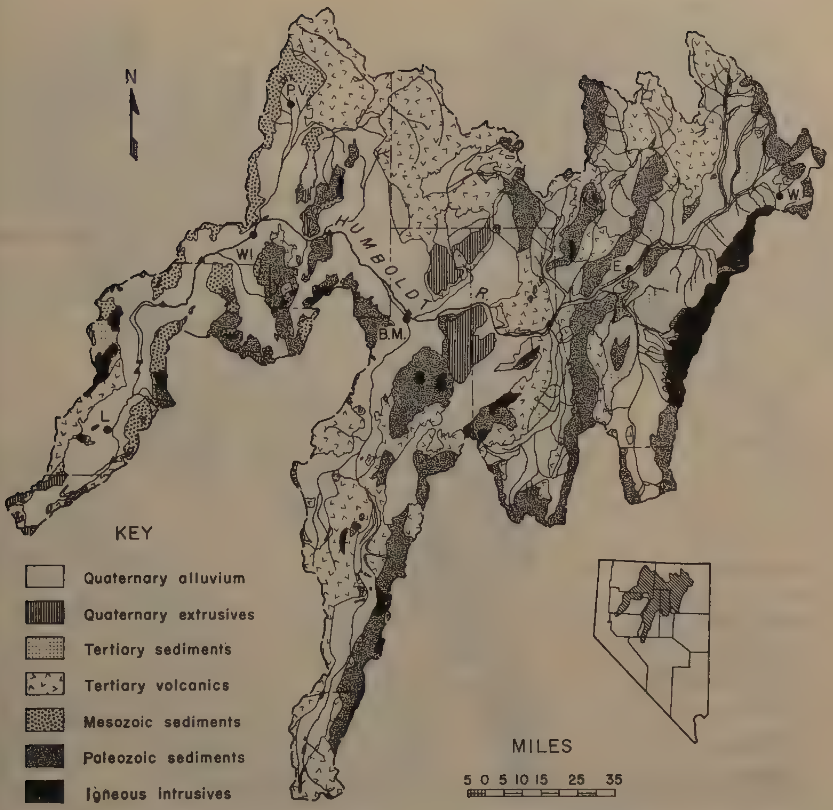

Fig. 2 — Geology of the Humboldt Basin. Compiled from maps of the U.S. Geological Survey and the Nevada State Bureau of Mines.

Mesozoic as well as Paleozoic sediments form a prominent part of the highlands. The valleys of downstream units comprise a proportionately larger fraction of total area and contain more and thicker alluvial fill. Hydrogeologically this is significant because the permeable alluvial-filled basins offer large volumes of storage space for ground water and appreciably affect flow of the river and its tributaries. Variations in geology and pattern of mountain ranges interspersed with broad alluvium-filled basins are diagnostic factors in designation of units and sub-units of the Basin.

Another factor is the distribution of precipitation shown in Figure 3. The map was compiled by George Hardman of the Nevada Department of Conservation and Natural Resources and is based upon all known sources of precipitation data, including conventional long-period weather stations, temporary stations and snow-survey courses. As shown in figure 3, the Upper Valley unit is a more or less typical semi-arid province with the annual precipitation ranging from 8 to more than 20 inches and with large areas in which the precipitation exceeds 12 inches. Precipitation decreases westerly and the western side of the Basin is arid with large areas of less than 5 inches of annual precipitation.

Figure 3 also illustrates the topography of the Basin quite accurately because

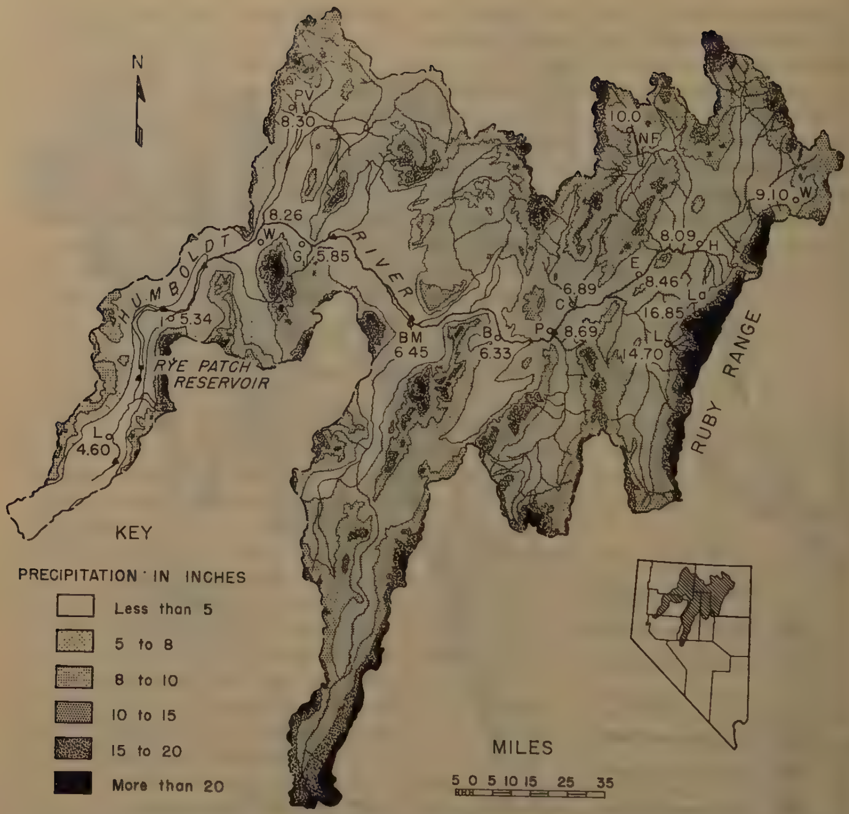

Fig. 3 — Distribution of Precipitation, Humboldt Basin. Compiled by George Hardman, Assistant Director, Rept. of Conservation and Natural Resources, State of Nevada.

amount of precipitation depends considerably upon elevation. Thus, the dark areas are regions of high elevation ranging from about 9,000 to over 11,000 feet, the white areas are on the order of 4,000 to 6,000 feet and other areas are intermediate in elevation.

The combined effects of distribution of precipitation and lithology result in broad hydrologic variations. For example, the Humboldt River is a gaining stream in the Upper Valley unit and a losing stream farther westward primarily because of these factors and the added factor of increased evaporation opportunity to the west. Also, changes in flow of the river and in storage in ground-water reservoirs within the Winnemucca unit probably result in large part from the distribution of differing lithologies.

The detailed geologic and hydrologic work in the Winnemucca unit has given us considerable insight into these problems. In order to remain within the limitations of space and time allotted for this paper only a summary of the work and its results is possible.

Figure 4 is a detailed geologic map of the central part of the Winnemucca unit. This area, in which mapping of surficial geology is essentially completed, presents

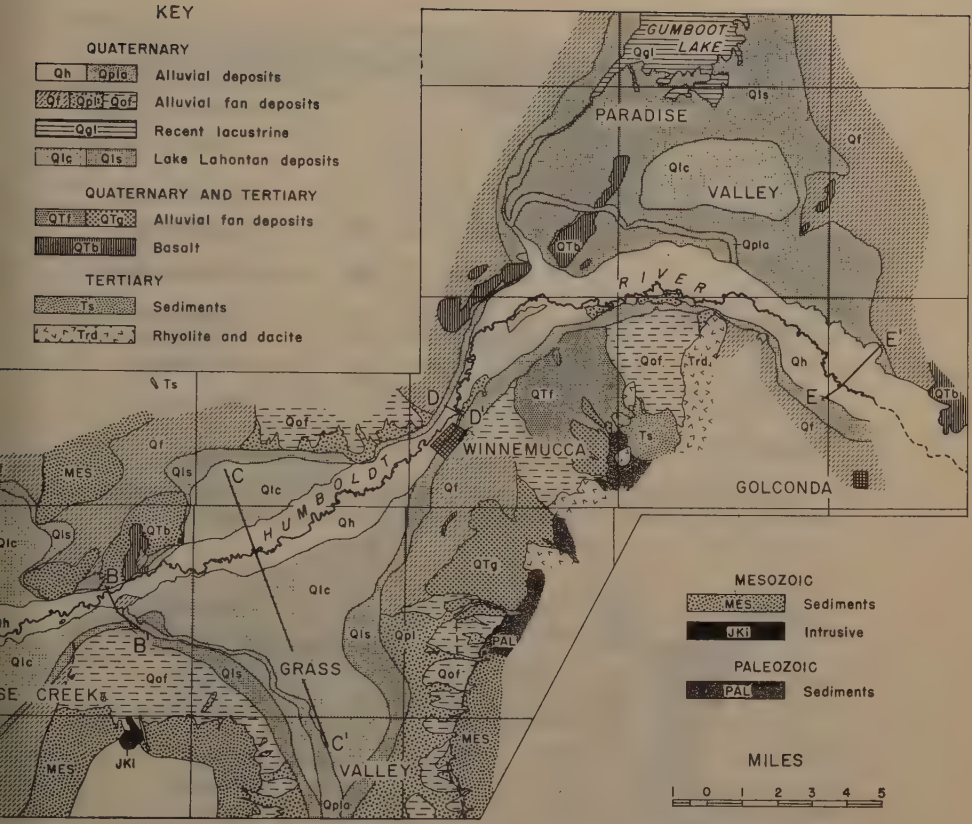

Fig. 4 — Geology of the Winnecuma unit, Humboldt Basin, Nevada. Geology by John W. Hawley, William E. Wilson and Keros Cartwright.

a good example of necessary detail of geologic mapping deemed adviseable for analysis of water resource problems. In addition to this mapping, much shallow subsurface analysis has been accomplished as illustrated in profiles shown in figures 5 and 6. Much of this detail in mapping and analysis was made possible by a test-drilling program conducted by the U.S. Geological Survey in which 160 shallow wells (a few feet to 117 feet deep) were bored, primarily in the river channel and environs. The shallow drilling program has resulted in much valuable knowledge. Drilling information is the basis for determination of specific yield of shallow sediments and other valuable hydrologic determinations, a primary aim of the Geological Survey study. It has confirmed the presence, extent, and thickness of an important sand and gravel aquifer which underlies the river channel from Golconda to Rose Creek. Further results of test-drilling include more intimate knowledge of the river channel materials and other sediments and their mutual relationships. These results show that the standard of detailed mapping is justified in this area in order to solve hydrologic problems. They also demonstrate the need for deeper test drilling to assist in outlining extent, distribution, and characteristics of deeper aquifers in the alluvial fill.

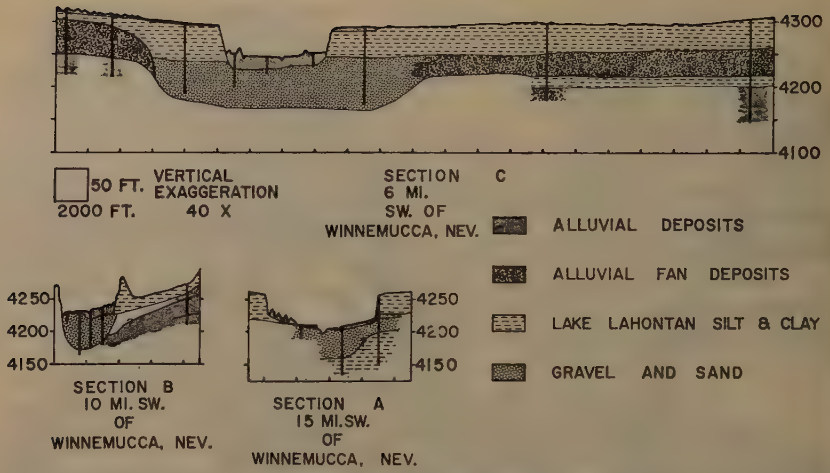
4300
4200
4100
50 FT.
2000 FT.
VERTICAL EXAGGERATION 40 X
SECTION C
6 MI. SW. OF WINNEMUCCA, NEV.
ALLUVIAL DEPOSITS
ALLUVIAL FAN DEPOSITS
LAKE LAHONTAN SILT & CLAY
GRAVEL AND SAND
4250
4200
4150
SECTION B
10 MI. SW. OF WINNEMUCCA, NEV.
4250
4200
4150
SECTION A
15 MI. SW. OF WINNEMUCCA, NEV.

Fig. 5 — Geologic profiles A, B, and C, Winnemucca unit. Modified from work by John W. Hawley, Wm. E. Wilson and Keros Cartwright.

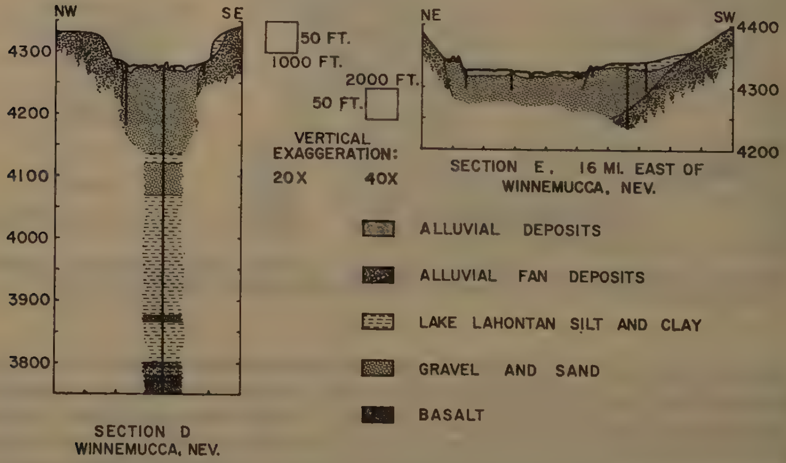

Fig. 6 — Geologic profiles D and E, Winnemucca unit. Modified from work by John W. Hawley, Wm. E. Wilson, and Keros Cartwright.

In conjunction with detailed geologic and geohydrologic studies the Geologica Survey has made a number of stream measurements in reaches of the river between Comus and Rose Creek to assist in determining relationships of stream flow, groundwater, and geologic controls. Preliminary data show that the river is a losing stream during high flow but that it gains and loses in different reaches across the unit (figure 7) during low flow. Preliminary piezometric-surface maps of ground water show verifying relationships, and study is now progressing to relate the geological data with this pattern. It is hoped that detailed study along these lines will result in an explanation for variations in losses from the river between Comus and Rose Creek.

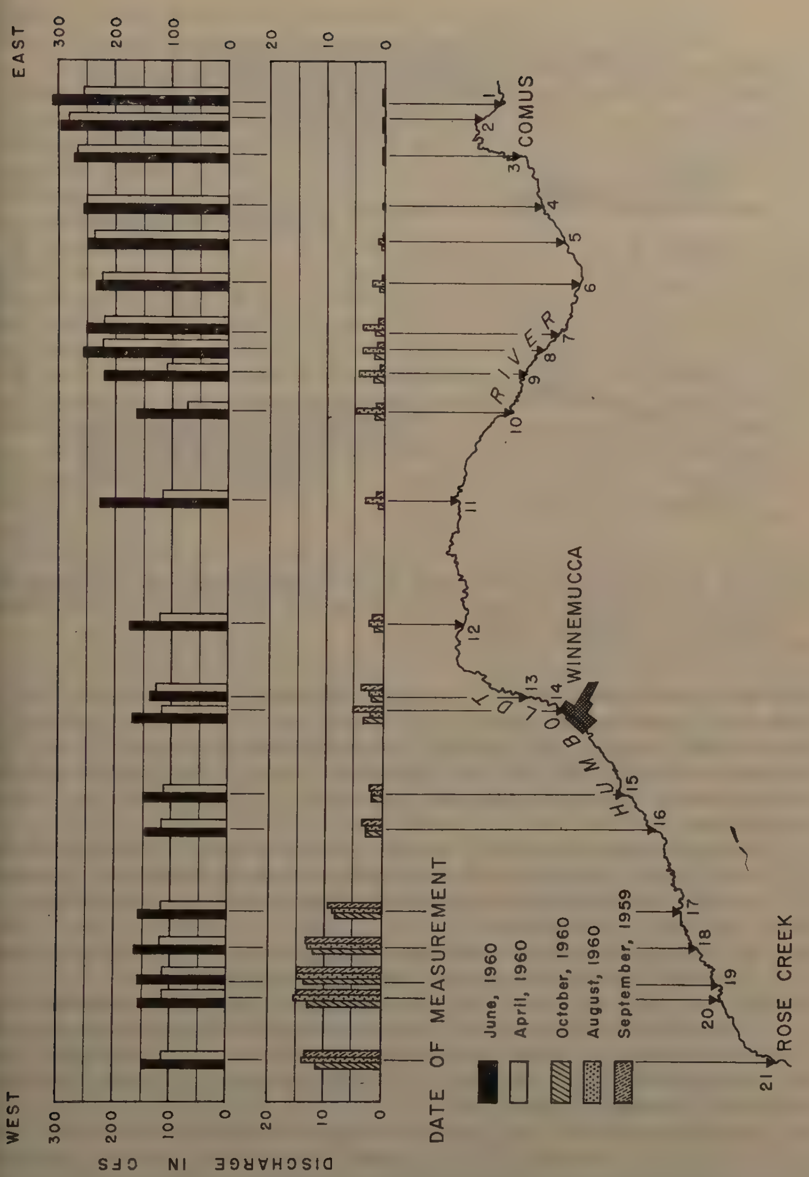

Fig. 7 — Stream Flow, Humboldt River. Compiled from measurements made by the U.S. Geological Survey.

Some generalizations can be made regarding stream flow and regimen from presently available data. Initial studies of available streamflow records give a gross estimate of the distribution and quantity of water potentially available from the Humboldt River and its tributaries. Figure 8 shows hydrographs of stream flow plotted on a logarithmic scale at four gaging stations on the river between Palisade

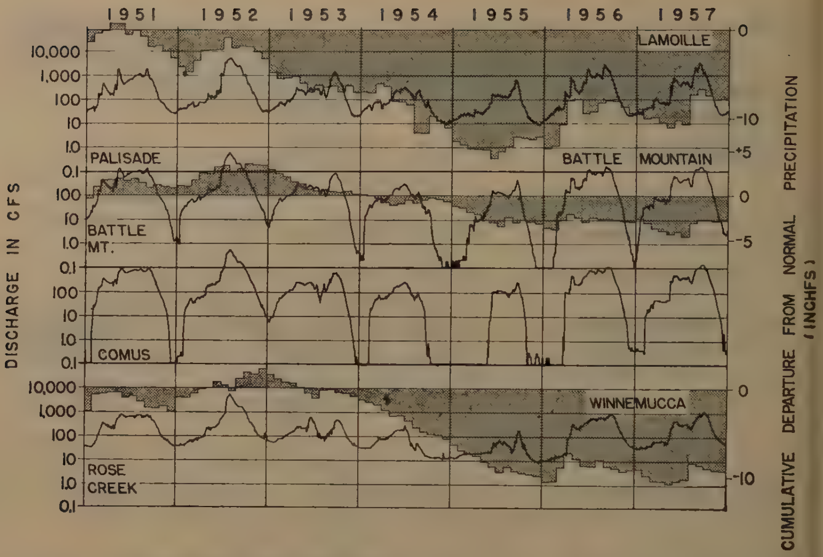

Fig. 8 — Hydrographs of the Humboldt River at four stations and C D from N P from three stations. Compiled from records of the U.S. Geological Survey and the U.S. Weather Bureau.

and Rose Creek, about 16 miles west of Winnemucca. The hydrographs, showing daily flow in cubic feet per second, were selected for a more or less representative period which includes both high and low stages between October 1, 1951 and September 30, 1957. Thus, not only seasonal but long-term fluctuations of stream flow are shown. Several fundamental characteristics of the nature of the stream flow appear:

1. Most of the stream-flow is snow melt normally appearing from November to January, cresting in the late spring, and rapidly falling off during the months of June and July to a base flow that is sometimes only a fraction of a percent of flood flow.
2. A consistent loss occurs between each gaging station from Palisade downstream. This will be discussed in succeeding paragraphs.
3. Where the stream flows over bedrock or other impermeable sediments as at Palisade and Rose Creek, it is perennial, even in low years, whereas at stations in alluvial areas where considerable bed loss can occur, the stream flow drops to little or nothing during considerable periods in the summer, as at Battle Mountain and Comus.
4. Long-term variations in peak flow are great, ranging from as much as 5,930 cubic feet per second during the record high in 1952 to only 330 cubic feet per second during a near-record low crest in 1954 at Palisade. Considerable variations in base flow also occur. Comparable relationships are shown at other stations.

Since the river is essentially uncontrolled throughout its course from the headwaters to Imlay, even simple and unsophisticated analyses such as these illustrate the nature of the river and of the primary water resources problem—a regimen consisting of one to three, more or less destructive floods in each decade interspersed by perhaps the same number of low flow years with resulting drouth conditions. The effects of drouth are especially severe when dry years occur in succession as they did in 1954 and 1955 and in 1959 and 1960.

The linear-scale block diagrams in figure 8 give cumulative departure from normal monthly precipitation for three stations. Close correlation between stream flow and precipitation is evident from comparison of these diagrams with stream flow. Further, the diagrams indicate that the period 1951 to 1957 was one of deficient precipitation within the period of record, especially in the headwaters area of the river where nearly all streamflow originates. Values for normal monthly and annual precipitation is given in Table 1 for comparison.

The diagrams in figures 9, 10, and 11 give values of annual discharge in acre-feet plotted on a logarithmic scale at stations from Palisade downstream. With these values are block diagrams on a linear scale showing apparent stream losses in acre feet from station to station for the period 1949 to 1960. During this period, the only one with relatively complete records on which to evaluate these losses, streamflow and losses are probably somewhat lower than actual long range values because flow averages for the period are somewhat lower than flow averages for longer periods of record. For example, average annual flow at Palisade over a period of 53 years averages 257,000 acre-feet and for the 12-year period the average is 240,500 acre-feet; at Comus for a period of 46 years it is 200,800, for the 12 years, 173,085; at Rye Patch for 46 years it is 144,100, for the 12 years, 130,500. Table 2 gives values on which the graphs in figures 9, 10, and 11 are based.

The values given in the table and figures are adjusted for total inflow and outflow at and below each gaging station. Thus, flow of Pine Creek and Rock Creek are added to Palisade, and flows of Kelly and Evans Creeks and estimates of underflow from Paradise and Grass Valleys are added to Comus. Losses in Paradise and Grass Valley, Reese River Valley (Waring, 1918, p. 110), and in the Rock Creek drainage area above the gaging station are not considered here since they do not appreciably affect, or are affected by stream flow in the main valley. The graphs and table show that during the twelve-year period losses averaged about 72,000 acre-feet annually between Palisade and Battle Mountain, 26,000 acre-feet between Battle Mountain and Comus, 24,000 acre-feet between Comus and Rose Creek, 8000 acre-feet between Rose Creek and Imlay, 26,500 acre-feet from Rye Patch Reservoir (Imlay to Rye Patch), and 42,000 acre-feet below Lovelock. Thus, the total average annual losses along the River, exclusive of the Upper Valley Unit approximate 198,000 acre-feet.

Several subsidiary factors are also shown by figures 9, 10, and 11. For example, losses between Palisade and Comus show an expectable pattern of low loss during low flows and high loss during high flows. However, between Comus and Rose Creek a different pattern appears. Losses seem to decrease with increasing flows and increase with decreasing flows with some lag. In one year, 1958, a gain between the stations is indicated. This problem is now being studied and undoubtedly answers will be forthcoming. It is believed that water stored in larger quantities in groundwater aquifers during high flows may return slowly to the river during drouth periods.

In figure 11, the losses between Imlay and Rye Patch chiefly represent evaporation from the Reservoir. Preliminary calculations show that the rate of evaporation on this basis may be on the order of three to four feet annually.

Not all losses determined above can be considered available for recovery because some water is now beneficially used and some is and inevitably will be economically unrecoverable. The amount of water beneficially used in the Basin below Palisade, in addition to that withdrawn from the Rye Patch Reservoir, is difficult to determine. However, on the basis of available information perhaps 60,000 acre-feet are used for crops and for domestic and stock purposes. This estimate is based on the assumption that the use of water from Rye Patch Reservoir is an acceptable standard of beneficial use.

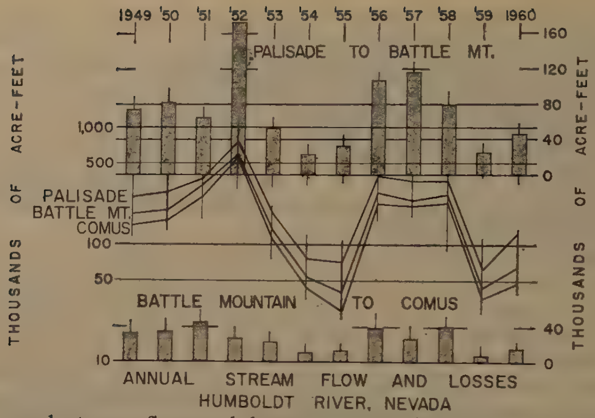

Fig. 9 — Annual stream flow and losses, Humboldt River, Nevada. Compiled from records of the U.S. Geological Survey.

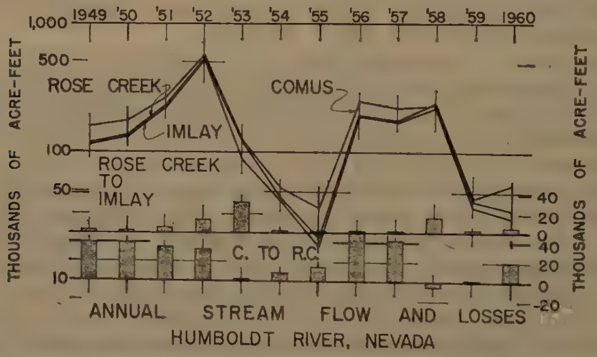

Fig. 10 — Annual stream flow and losses, Humboldt River, Nevada. Compiled from records of the U.S. Geological Survey.

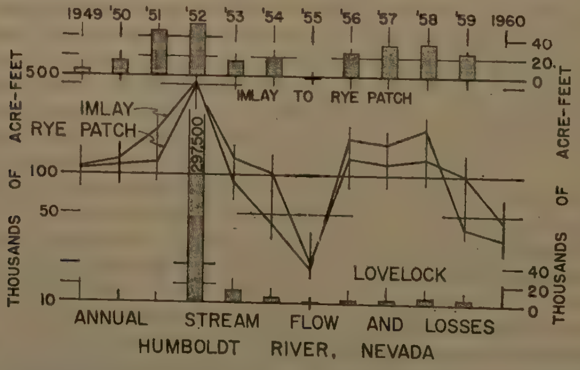

Fig. 11 — Annual stream flow and losses, Humboldt River, Nevada. Compiled from records of the U.S. Geological Survey.

TABLE 1

Normal monthly and annual precipitation at four stations in the Humboldt Basin. Compiled from records from the U.S. Weather Bureau.

	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Lamoille	1.46	1.56	2.01	2.67	2.17	1.48	.74	.50	.76	1.48	1.61	1.72	18.16
Battle Mountain	.79	.71	.65	.75	.80	.54	.18	.15	.27	.53	.57	.77	6.71
Lovelock	.82	.71	.54	.53	.46	.62	.13	.14	.20	.54	.42	.65	5.76
Winnemucca	.96	1.01	.86	.83	.84	.79	.31	.18	.34	.79	.84	1.00	8.75

Water known to be lost for essentially any further use includes reservoir losses at Rye Patch, on the order of 26,500 acre-feet and that part of the water which flows into the Humboldt "Sink" in return flow from irrigation in the vicinity of Lovelock, about 4,500 acre-feet. The remainder of the flow downstream from Lovelock is flood water which cannot presently be controlled by the Reservoir, and constitutes perhaps as much as 300,000 acre-feet every ten years. This water, or a large fraction of it could conceivably be intercepted and stored upstream and is considered available for recovery.

In summary, about 91,000 acre-feet of water plus that used from Rye Patch Reservoir (130,000 acre-feet) is not available for recovery, leaving approximately 100,000 acre-feet of water as the potentially recoverable losses between Palisade and Humboldt "Sink" (Table 3).

TABLE 3

Inventory of water losses, water beneficially used or not recoverable, and water potentially available in the Humboldt Basin below Palisade. Potentially available water does not include all potential return flow.

From	To	Water losses	Water Beneficially Used	Water not Recoverable	Water Potentially Available
Palisade	Battle Mtn.	72,000	60,000	?	70,000
Battle Mtn.	Comus	26,000		? ?	
Comus	Rose Creek	24,000		?	
Rose Creek	Imlay	8,000		?	
Imlay	Rye Patch	26,500	130,500	26,500	0
Passing	Lovelock station	42,000		4,500	37,500
	Total	198,500	190,500	31,000	107,500

Comparison of this value with the roughly estimated beneficial use of river water in the Basin today, about 130,000 acre-feet from Rye Patch Reservoir and 60,000 acre-feet in the Valley between Palisade and the Reservoir, indicates that something on the order of 50 per cent more water is available for recovery. This estimate does not include water that might be salvaged or more efficiently used if material changes are made in the economy of the Basin.

The purpose of this simple analysis is primarily to show the variety and magnitude of problems being considered by the Project. Its results are most certainly not to be considered as dependable for justifying construction of controls, employment of management, or for recommending changes in the economy. On the other hand, the results are deemed to justify further research to determine more dependable values for guidance in development of the Basin.

TABLE 2

Annual stream flow and losses in acre-feet at gaging stations in the Humboldt Basin. All measurements from records of the U.S. Geological Survey.

Water Year	Palisade, Rock Cr., & Pine Cr.	Battle Mtn.	Losses between Palisade and Battle Mtn.	Comus	Losses between Battle Mtn. and Comus	Losses — Battle Mtn. Unit	Comus, misc. creeks and underflow	Rose Creek	Losses — Winnemucca Unit	Imlay	Losses — Rose Creek to Imlay	Rye Patch Station (also represents use from Reservoir)	Losses-Rye Patch Reservoir (Imlay minus Rye Patch)		Lovelock	Losses — Lovelock Unit	Total Losses — Humboldt Basin below Palisade
													Unadjusted	Adjusted for changes in storage			
1949	254,610	181,200	73,410	148,500	32,700	106,110	158,500	118,500	40,000	115,600	2,900	111,000	4,600	21,050	—	—	—
1950	281,500	199,000	82,500	164,900	34,100	116,600	174,900	135,000	39,900	132,400	2,600	118,300	14,000	20,590	—	—	—
1951	368,680	302,700	65,980	257,700	45,000	110,980	267,700	232,700	35,000	226,600	6,100	124,500	102,100	45,750	—	—	—
1952	760,750	587,100	173,650	558,500	28,600	202,250	568,500	535,800	32,700	522,200	13,600	408,600	113,600	52,980	297,500	364,080	599,030
1953	186,300	134,300	52,000	112,100	22,200	74,200	122,100	120,100	2,000	87,810	32,290	135,700	47,890	14,950	11,940	59,180	135,380
1954	77,350	53,980	23,370	43,590	10,390	33,760	53,590	44,270	9,320	41,050	3,220	103,000	61,850	19,960	5,840	29,020	72,100
1955	70,890	39,460	31,430	27,530	11,930	43,360	37,530	21,840	15,690	18,830	3,010	21,170	2,340	1,776	1,350	2,584	61,634
1956	386,130	278,800	107,330	240,200	38,600	145,930	250,200	197,200	53,000	193,400	3,800	137,700	55,700	25,296	3,760	32,856	231,786
1957	353,090	239,800	113,290	213,500	26,300	139,590	223,500	180,800	42,700	177,700	3,100	123,000	54,700	33,130	4,150	40,380	222,670
1958	348,840	269,000	79,840	228,800	40,200	120,040	238,800	243,200	4,400	226,500	16,700	135,200	91,300	35,160	6,620	58,480	174,120
1959	62,390	41,870	20,520	34,910	6,960	27,480	44,910	42,650	2,260	38,330	4,420	103,000	64,770	25,180	5,350	34,950	64,690
1960	102,760	62,170	40,590	46,800	15,370	55,960	56,800	36,290	20,510	31,510	4,780	44,730	13,220	—	—	—	—
12-yr. Av.	271,107	199,105	71,992	173,085	26,029	98,021	183,085	159,029	24,056	150,994	8,043	130,491	20,494	26,570	42,063	77,691	198,753

4. METHODS OF RECOVERY AND REGULATION

In view of present limitations on our knowledge, discussion of all possible methods of recovery and regulation of water in Humboldt Basin is premature, however, important aspects of the problem and some consideration of them can be profitably mentioned. On the basis of available analyses and data, the key to recovery and beneficial use of a considerable amount of water obviously lies in regulation of river-flow by some method or combination of methods of storage. Additional recovery, perhaps the bulk of it, may be accomplished by diversion of water to beneficial uses from use by non-beneficial phreatophytes and other evapotranspiration losses.

Development of additional storage in surface reservoirs has been under study by various agencies and is now being considered by members of the Project. The river basin study to determine small drainage storage sites will yield much needed information. Studies by State and Federal Agencies aimed at locating and determining feasibility of large reservoirs have shown that few sites, chiefly in the Upper Valley unit, are available and that these are limited in potential utility by a very small cost-benefit ratio. Further, development of surface storage would result in increased evaporation losses which might materially offset advantages gained. Quantitative limitations of this method are under study but have not been determined.

Possible methods of diverting evapotranspiration losses to beneficial use are also under study. Preliminary steps to solve this problem have been described in a foregoing part of this paper.

Conjunctive use of surface flow and ground-water storage as a method of recovery and regulation is being carefully considered. One large ground-water reservoir in the Winnemucca unit and the probability of another of almost similar size in the Battle Mountain unit, both of which underlie or are adjacent to the river, afford possible storage sites. Presently estimated volume that might be made available for storage is on the order of at least 500,000 acre-feet. At present these ground-water reservoirs are saturated to river level and only during times of high flow is storage in them advantageously used, apart from limited withdrawals for irrigation, municipal and domestic purposes. Carefully controlled withdrawal of large quantities of ground water, perhaps as much as 400,000 acre-feet in the Winnemucca Unit, might result in a water-level decline on the order of 40 to 50 feet and would make available enough storage space to accommodate nearly two years of average flow of the river. Adequate data for estimates are not yet available but storage on the order of one-half to two-thirds of this capacity might be developed in the Battle Mountain unit.

If water levels in ground-water reservoirs of the Winnemucca and Battle Mountain units could be maintained at depths exceeding 25 feet, evaporation opportunity would be greatly reduced since the stored water would be underground and out of reach of the most wasteful of the non-beneficial phreatophytes.

Presently we need more physical facts on geometry and lithology of these aquifers and more knowledge of recharge processes and methods. Recharge basins in southern California are being successfully used to inject water in underground reservoirs. Rates as high as one foot per day are not uncommon. Therefore, members of the Project will continue to study and evaluate conjunctive use of surface and ground water in the Humboldt Basin. Probably this method offers the most promising potential to recover the greatest amount of water now lost to evapotranspiration and flood run-off and to modulate river flow.

REFERENCES CITED

Fredericks, J. C., and Loeltz, O. J., 1951, *Ground water in the vicinity of Elko, Nevada in Contribution to the Hydrology of Eastern Nevada* : Office of the Nevada State Engineer, Water Resources Bull. No. 12, p. 39-63.

Loeltz, O. J., Phoenix, D. A., and Robinson, T. W., 1949, *Ground Water in Paradise Valley, Humboldt County, Nevada* : Office of the Nevada State Engineer, Water Resources Bull. No. 10, 61 p.

Mashburn, Gray, and Mathews, W. T., 1943, *The Humboldt River Adjudication, 1923-1938* : State of Nevada, Office of the Attorney-General, Section no. 1, 250 p., Section no. 2, 22 p., Section no. 3, 108 p., Section no. 4, 17 p., Section no. 5, 12 p.

Nevada State Department of Conservation and Natural Resources, 1960, *Progress Report — Humboldt River Research Project* : mimeo. rept., 42 p.

Nevada State Department of Conservation and Natural Resources, 1961, *Second Progress Report — Humboldt River Research Project* : mimeo rept., 39 p.

Robinson, T. W., and Fredericks, J. C., 1946. *Ground water in Lovelock Valley, Nevada* : Office of the Nevada State Engineer, Water Resources Bull. No. 2, 25 p.

Waring, G. A., 1918, *Ground Water in Reese River Valley and adjacent parts of Humboldt River Valley, Nevada* : U.S. Geological Survey Water-Supply Paper 425-d, p. 95-129, pls. 7-12.

HYDROGEOLOGICAL COMPUTATIONS OF EXPLOITATION RESOURCES OF UNDERGROUND WATERS FOR LARGE WATER SUPPLY

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Résumé

1. L'évaluation des ressources exploitables des eaux souterraines est basée sur des supputations de la productivité des pompages. D'après les résultats de ces calculs on établit le volume d'eau qui peut être obtenu de la nappe (ou des systèmes de nappes) de cette région durant la période complète d'exploitation.

Le choix du type et de l'installation des stations de pompage est fait en tenant compte des conditions techniques et économiques.

2. Les conditions pour cette évaluation comprennent les éléments suivants :

a) structure géologique, composition et perméabilité des couches porteuses;

b) forme géométrique et étendue de la couche porteuse;

c) recharge en eaux souterraines dans les conditions naturelles avant les pompages et après leur mise en exploitation.

3. Le système de pompage peut aussi être schématisé, par exemple en étudiant un système de puits nombreux ayant des actions réciproques, des galeries, des puits importants, etc.

4. L'évaluation de la productivité des installations de pompage est faite par des méthodes analytiques en tenant compte de la complexité considérable de la structure réelle avec l'aide de méthodes approchées.

Dans le premier cas, l'évaluation du décit et du rabattement est faite d'après la solution des équations différentielles du mouvement de l'eau souterraine en tenant compte des conditions aux limites dérivant de l'ensemble des conditions naturelles ainsi que du schéma et du régime de l'exploitation par pompage.

Les méthodes d'approximation sont basées sur le pompage expérimental et sur les déductions de l'étude du régime des eaux souterraines et de surface.

5. Des relations pour l'évaluation pour divers cas de pompage sous des conditions naturelles différentes sont présentées et des exemples de leur application sont donnés.

Abstract

1. The evaluation of exploitation resources of underground waters is based on computations of the productivity of waterpumping constructions.

According to the results of such calculations the amount of water is established which may be collected from the strata (or system of stratas) on this or that area of its distribution during the whole period of exploitation of waterpumping constructions.

The choice of the type and the design of water-pumping constructions is done in relation to natural and technical and economical indexes.

2. The natural conditions for computations are summarized in a definite way and represented in the form of so-called «computational schemes».

The main elemenst reflected in computational schemes are:

a) geological structure, composition and water permeability of aquifers;

b) geometrical sizes and the shape of an aquifer;

c) the sources of refilling the resources of underground waters under natural conditions before putting into operation water-pumping constructions and under the conditions of their exploitation.

3. The water-pumping constructions for computation of exploitation resources of underground waters can also be schematized. For instance, an opportunity is given (especially for approximate evaluation of resources in early stages of projecting) to study groups out of a great number of reciprocal wells in the form of «summarized systems»—«galleries», «big wells» and so on.

4. Computation of productivity of water-pumping constructions is made by analytical methods and also with considerable complexity of the real natural situation with the help of approximate methods.

In the first case the computational relationships for evaluating the yield and lowering of water table are made according to strict solutions of primary differential equations of the movement of underground waters under primary and border conditions defined by the complex of all natural factors as well as the scheme and regime of exploitation of water-pumping constructions taken.

Approximate methods are based on direct use of data of experimental pumping and correlated connections established according to the regime of underground and surface waters.

5. The computational relationships for different schemes of water-pumping constructions under different natural conditions are made in the paper and the examples of their practical application are given.

The exploitation resources of underground waters represent the amount of water which may be received from the bed (or system of beds by water-pumping constructions rational in technical and economic aspects during a certain period of time designed beforehand when the quality of water is preserved within the conditions required (N. A. Plotnikov, 1948, 1956; G. N. Kamensky, 1948; F. M. Bochever, 1958).

The exploitation resources are ensured by the following sources:

a) The natural resources of the exploited bed (the discharge of the flow moving through the bed and the volume of water contained in pores and fractures of the rock);

b) Water filtration from natural and artificially created surface stream flows and water reservoirs;

c) The flow of the water through upper and lower beds with low water permeability from the adjoining waterbearing strata;

d) Draining of upper and lower beds with low water permeability.

The role of each of above-mentioned sources in the total value of exploitation resources may be evaluated separately. However, in many cases it is connected with great difficulties. In practice the method of forecasting the total value of exploitation resources by means of computing the possible efficiency of water-pumping constructions and lowering of the water table of underground waters as a result of their activities is more advisable and easy to use (F. M. Bochever and N. N. Verigin, 1961).

This task is usually solved by means of a number of consequent approximations. For instance, when the water pumping constructions consist of wells (*), the total discharge and the discharge of each well, their sizes and the distance between them are evaluated; the lowering of the water table S is established by the end of the designed period of exploitation t.

The relationship $S \approx S_{pos}$ must be maintained, where S_{pos} is the permissible lowering of the level in water-pumping constructions defined according to technical and hydrogeological conceptions.

Under $S > S_{pos}$ the designed yield of the water-pumping construction cannot be considered ensured. In this case it is necessary either to increase the number of wells decreasing their yield or distribute wells at a big area.

On the contrary under $S < S_{pos}$ the yield of the water pumping construction may be increased or when the design yield is maintained, the number of wells may be decreased and the distance between them reduced.

The natural conditions are taken into account when out-laying water-pumping constructions; they are schematized and presented in the form of so called "design schemes" for design aims (F. M. Bochever, 1959, F. M. Bochever and N. N. Verigin, 1961).

Design schemes reflect:

a) geological structure, composition and water permeability of water-bearing rocks;

(*) Further we discuss only pumping out of wells.

b) geometrical sizes and the shape of water-bearing strata;

c) the sources of replenishment of resources of underground waters under natural conditions before putting into operation water-pumping constructions and when exploiting them.

When taking into account all above-mentioned factors the results of design of all water-pumping constructions characterize not only their technical opportunities but also the replenishment of the resources of underground waters utilized.

When computing, the water-pumping constructions as well as the natural conditions are schematized. In particular it is advisable, for instance, to regard groups of more or less considerable number of interference wells as "summarized systems"-"galleries", a "big well" and so on (V.N. Shchelkachev, 1948, 1952, N.S. Piskunov, 1954, V.M. Shestakov, 1958, N.N. Pavlovskaya, 1959, F.M. Bochever, 1961).

In this way the process of computation is simplified.

Let us regard the procedure of computing summarized systems of interference wells by analytical relationships, received from the solution of initial differential equation of filtration, and by empirical formulae which may be built on the basis of trial and exploitation pumpings.

1. COMPUTATION OF WATER-INTAKES BY ANALYTICAL RELATIONSHIPS

It is known that the movement of underground waters may be described by the following differential equation which is analogous to the equation of heat conductivity (V.N. Shchelkachev, 1946, P.Ya. Polubarinova-Kochina, 1952).

$$a\left(\frac{\partial^2 \mathcal{U}}{\partial x^2}+\frac{\partial^2 \mathcal{U}}{\partial y^2}\right)=\frac{\partial \mathcal{U}}{\partial t}, \qquad (1.1)$$

where $\mathcal{U}$ is a "head function" or "lowering function".

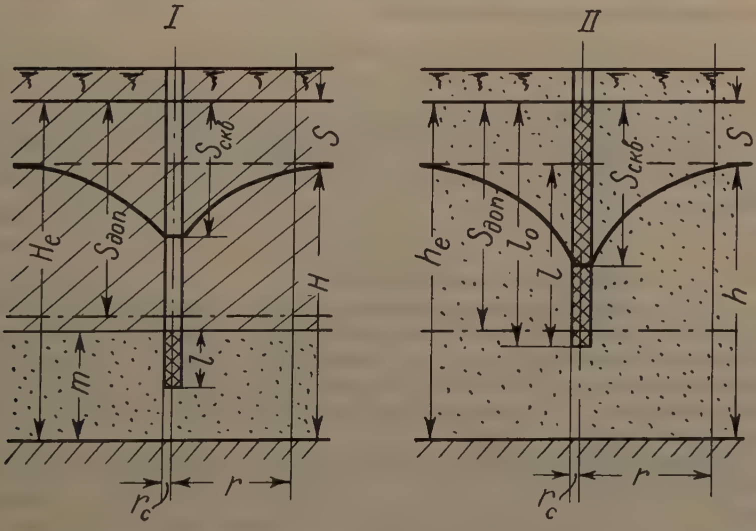


Fig. 1

For head waters (fig. 1)

$$\mathcal{U} = mS = m(H_e - H), \text{ from thir } S = \frac{\mathcal{U}}{m} \tag{1.2}$$

For waters with free surface (N.N. Verigin, 1957, I.A. Charny, 1956)

$$\mathcal{U} = \left(h_e - \frac{S}{2}\right) S = \frac{1}{2}\left(h_e^2 - h^2\right) \text{ or } S = h_e - \sqrt{h_e^2 - 2\mathcal{U}} \tag{1.3}$$

In these expressions:

S is lowering of the level in any point of the bed with coordinates x, y at any moment of time t;

H and h is the head (in pressure waters) and the depth of water before the confining bed (in waters with free surface) at the same point at the same moment of time;

H_e and h_e are correspondingly the preliminary head and the depth of water at this point (so called "statistical levels" before putting into operation the water-pumping construction).

Coefficient a which is involved in the equation (1.1) is named as piezoconductivity coefficient.

For beds with free surface (*)

$$a = \frac{K.h_{av}}{\mu} \tag{1.4}$$

where K is a coefficient of permeability;

h_{av} is the average thickness of the bed (for tentative computation $h_{av} \approx 0{,}7\, h_e$);

μ is a coefficient of water yield of the bed during its draining.

The coefficient of piezoconductivity for non-artesian beds, for instance, when the thickness of the bed $h_e = 15 - 20$ m for fine sands equals to 250-500 m^2/day and to 2000-4000 m^2/day for coarse gravel sands.

For artesian beds the coefficient of piezoconductivity may be formally presented in the same form as for non-artesian beds:

$$a = \frac{Km}{\mu^*} \tag{1.5}$$

Here K and m are coefficient of permeability and the thickness of the bed;

μ^* is an index which also characterizes "the water yield" from the bed which it is common to explain by elastic properties of the water itself and the water-bearing rocks.

$$\mu^* = \gamma\beta_m^* \tag{1.6}$$

where γ is the weight of the water volume unit;

β^* is a coefficient of volume elasticity (V.N. Shelkochev, 1946, 1948, 1959).

The value of the coefficient of piezoconductivity for head flows of fresh underground waters, containing no gas, within the limits of dense rocks with good water permeability makes up 10^5-10^6 (m^2/day). In fine-grained ("loose") rocks with low water permeability it may fluctuate within considerable range from $n.10^3$ to $n.10^4$ (m^2/day) ($n = 1 \div 10$).

To define the piezoconductivity according to the data of trial pumping out of wells is more reliable.

(*) For non-artesian beds it is also common to call as a coefficient of level conductivity (V.M. Shestakov, 1956).

The solution of the differential equation (1.1) related to the water-pumping constructions may be presented in such a general form (F. M. Bochever, 1959, 1961, F. M. Bochever and N. N. Verigin, 1961).

$$\mathcal{U} = \frac{Q_{tot.}}{4\pi k} R (1,7) \text{ or } Q_{tot.} = \frac{4\pi k \mathcal{U}}{R} \tag{1.8}$$

Here $Q_{tot.}$ is the total discharge of the water-pumping construction;

R is a function which characterizes the hydraulic resistance. It is divided into two parts:

$$R = R_r + R_{ckb} \tag{1.9}$$

where R_r is "outward" hydraulic resistance, which depends on the type of water-pumping construction, the size of the water-bearing bed, conditions at its borders, piezoconductivity coefficient and the duration of pumping;

R_{ckb} is "inner" hydraulic resistance, which is defined by the distance between wells, their sizes and the rate of imperfection.

In table no. 1 the calculated relationships, for defining the outward resistance R_{r0} related to the different types of water-pumping constructions in beds which are rather big by size (theoretically "infinite") in a space are given.

These relationships are received relying upon the premise about the permanency of the discharge of the water-pumping construction. In accordance with this the value $Q_{tot.}$ which is included into the equation (1.7) and (1.8) should be considered as discharge which must be maintained during a period of time t so that by the end of it the lowering of the level in the considered point reached the value S.

In table no. 1:

Ei is an integral model function $\left[Ei(-\lambda) = \int_{\lambda}^{\infty} \frac{l^{-u}}{\mathcal{U}} du\right]$

is Crump's function $[\Phi(\lambda) \int_{0}^{\lambda} l^{-u^2} du]$ (M. Yanke, and F. Emde, 1932).

Formulae (1.11)-(1.13) are real for above mentioned "summarized systems" that is when substituting the real wells by an infinite number of linear sources with a permanent discharge evenly ditributed over the line or area approximately corresponding to the actual line or area of location of wells.

The total discharge of these sources is equal to the total discharge of real wells.

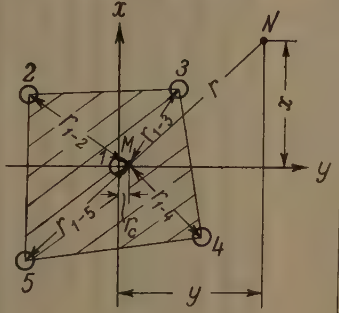
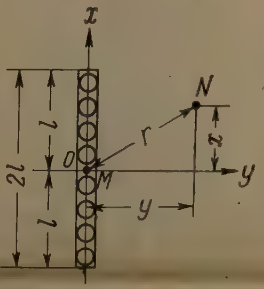
The formula (1.14) for summarized systems may be applied when defining the head function $\mathcal{U}$ (or lowering S of the level S) at points situated at a distance, exceeding half of the greatest extent of the water-pumping construction, that is under $r > 1{,}5\, r_{i\_max}$ for a group of randomly situated wells, $r > 1{,}5\ l$ and $r > R_0$ for a group and round schemes.

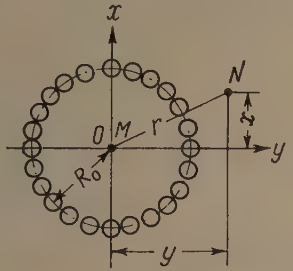
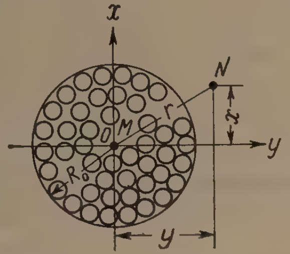
The formula (1.14) characterizes the activity of a single well. From this follows that the effect of the various groups of interterence wells already at a small distance from them is analogous to the effect of a single well with the same total discharge.

This circumstance rather simplifies the task of computing the interference wells in beds confined by recharge boundary (or run-off) and impermeable boundaries. Availing themselves of the method of mirror reflection, the reflected ("imagined") groups in these cases may be substituted by single wells. When computing several in linear interference groups of wells the same practice can be used.

Table no. 2 gives computed relationships, received in this way, for defining outward hydraulic resistance (R_{rk}) in finite beds (F. M. Bochever, 1961).

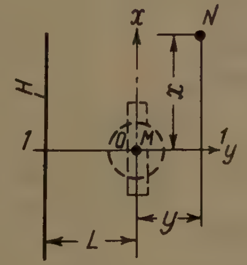
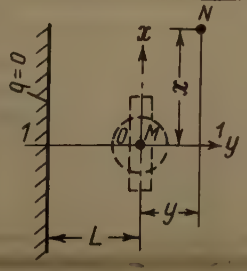
TABLE No. 1

The type of the water-pumping construction		Relationships for defining			
		In the centre of water intake (point *M*)	N	At a distance from the water-pumping construction construction (point *N*)	N
A group of randomly situated wells	 x N 2 3 r r_{1-2} r_{1-3} M 1 x y r_{1-5} r_c r_{1-4} 4 5 y	$R_{r0} = -\sum_{i=1}^{n} \alpha_i E_i \left(-\frac{r_i^2}{4at}\right)$ $\alpha_i = \frac{Q_i}{Q_{tot}}$ (V.N. Shchelkachev, 1948, M. Muscat, 1949)(*)	(1.10)	$R_{r0} \approx -E_i\left(-\frac{r^2}{4at}\right)$ (I.A. Charny, 1956, F.M. Bochever, 1959, 1961)	
The linear system of wells		$R_{r0} = -E_i\left(-\frac{l^2}{4at}\right) +$ $+ \frac{2\sqrt{\pi at}}{l}\Phi\left(\frac{l}{2\sqrt{at}}\right)$ (N.S. Piskunov, 1954, L.N. Pavlovskaya, 1959, F.M. Bochever, 1959)	(1.11)		(1,14)

The type of the water-pumping construction		Relationships for defining R_{r0}			
		In the centre of water intake (point M)	N	At a distance from the water-pumping construction construction (point N)	N
The ring system of wells		$R_{r0} = -E_i\left(-\frac{R_0^2}{4at}\right)$ (V.N. Shchelkachev, 1948, M. Muscat, 1949, V.P. Pilatovsky, 1953)	(1,12)	according to (1,14)	
Round (areal) system of wells		$R_{r0} = -E_i\left(-\frac{R_0^2}{4at}\right) + \frac{4at}{R_0^2}\left[1 - \exp\left(-\frac{R_0^2}{4at}\right)\right]$ (N.S. Piskunov, 1954, I.A. Charny, 1956)	(1,13)	according to (1,14)	

(*) The inner resistance R_{r0} is partially included into R_{ckb} for a given scheme. See ref. on page 466 further.

TABLE 2

The type of the bed		Relationship for definition R_{rk}	N	Radii-vectors for reflecting			
				When defining R_{rk} in the centre of water intake (point M)	N	When defining R_{rk} at a distance from water intake (point N)	N
1		2	4	5	6	7	8
Ia A stratum with one boundary of recharge		$R_{rk} = R_{r0} + E_i\left(-\frac{\varrho^2}{4at}\right)$	(1,15)	$\varrho^2 = 4L^2$	(1.16)	$\varrho^2 = x^2 + (2L + y)^2$	(1.17)
Ib A stratum with one impermeable boundary		$R_{rk} = R_{r0} - E_i\left(-\frac{\varrho^2}{4at}\right)$ - - - - -	(1,18)	according to	(1.16)	according to	(1.17)

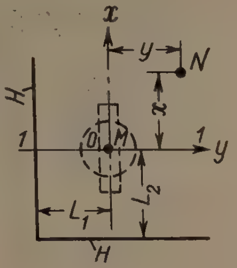
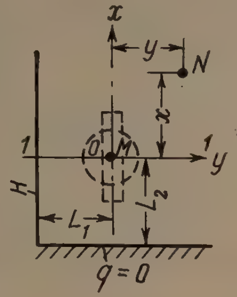
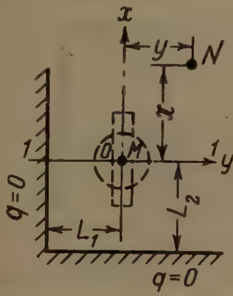
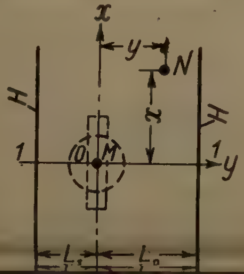
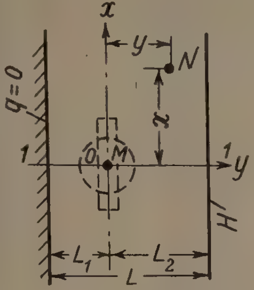
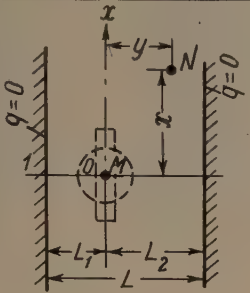
The type of the bed		Relationship for definition R_{rk}	N	Radii-vectors for reflecting			
				When defining R_{rk} in the centre of water intake (point M)	N	When defining R_{rk} at a distance from water intake (point N)	N
1		2	4	5	6	7	8
IIa A stratum with two intersecting boundaries of recharge	 x y N x H 1 0 M 1 y L1 L2 H	$R_{rk} = R_{r0} + E_i\left(-\frac{\varrho_1^2}{4at}\right) +$ $+ E_i\left(-\frac{\varrho_2^2}{4at}\right) - E_i\left(\frac{\varrho_3^2}{4at}\right)$	(1,19)	$\varrho_1^2 = 4\,L_1^2$ $\varrho_2^2 = 4\,L_2^2$ $\varrho_3^2 = 4(L_1^2 + L_2^2)$	(1,20)	$\varrho_1^2 = x^2 + (2\,L_1 + y)^2$ $\varrho_2^2 = (2\,L_2 + x)^2 + y^2$ $\varrho_3^2 = (2\,L_2^2 + x)^2 +$ $+ (2\,L_1 + y)^2$	(1,21)
IIb A stratum with two intersecting boundaries: boundary of recharge and impermeable boundary	 x y N x 1 0 M 1 y H L1 L2 q = 0	$R_{rk} = R_{r0} + E_i\left(-\frac{\varrho_1^2}{4at}\right) -$ $- E_i\left(-\frac{\varrho_2^2}{4at}\right) + E_i\left(-\frac{\varrho_3^2}{4at}\right)$	(1.22)	according to	(1.20)	according to	(1.21)

TABLE 2

The type of the bed		Relationship for definition R_{rk}	N	Radii-vectors for reflecting			
				When defining R_{rk} in the centre of water intake (point M)	N	When defining R_{rk} at a distance from water intake (point N)	N
1		2	4	5	6	7	8
IIc A stratum with two intersecting impermeable boundaries	 x y N x 1 0 M 1 y q=0 L₂ L₁ q=0	$R_{rk} = R_{r0} - E_i\left(-\frac{\varrho_1^2}{4at}\right) - E_i\left(-\frac{\varrho_2^2}{4at}\right) - E_i\left(\frac{\varrho_3^2}{4at}\right)$	(1.23)	according to	(1.20)	according to	(1.21)
IIIa A stratum with two parallel boundaries of recharge	 x y N H x H 1 0 M 1 y L₁ L₂	$R_{rk} = R_{r0} + E_i\left(-\frac{\varrho_1^2}{4at}\right) + E_i\left(-\frac{\varrho_2^2}{4at}\right) - E_i\left(-\frac{\varrho_3^2}{4at}\right) - E_i\left(-\frac{\varrho_4^2}{4at}\right) + E_i\left(-\frac{\varrho_5^2}{4at}\right)$	(1.24)	$\varrho_1^2 = 4L_1^2$ $\varrho_2^2 = 4L_2^2$ $\varrho_3^2 = 4L^2$ $\varrho_4^2 = 4L^2$ $\varrho_5^2 = 4(2L_1 + L_2)^2$	(1,25)	$\varrho_1^2 = x^2 + (2L + y)_1^2$ $\varrho_2^2 = x^2 + (2L_2 + y)^2$ $\varrho_3^2 = x^2 + (2L + y)^2$ $\varrho_4^2 = x^2 + (2L - y)^2$ $\varrho_5^2 = x^2 +$	(1,26)

The type of the bed		Relationship for definition R_{rh}	N	Radii-vectors for reflecting When defining R_{rh} in the centre of water intake (point M)	N	When defining R_{rh} at a distance from water intake (point N)	N
1		2	4	5	6	7	8
IIIb A stratum with two parallel boundaries: boundary of recharge and impermeable boundary	 x y N x 0=b 1 0 M 1 y H L1 L2 L	$R_{rk} = R_{r0} + E_i\left(-\frac{\varrho_1^2}{4at}\right) - E_i\left(-\frac{\varrho_2^2}{4at}\right) + E_i\left(-\frac{\varrho_3^2}{4at}\right) + E_i\left(-\frac{\varrho_4^2}{4at}\right) - E_i\left(-\frac{\varrho_5^2}{4at}\right)$	(1.27)	according to	(1.25)	according to	(1.26)
IIIc A stratum with two parallel impermeable boundaries	 x y N x 0=b 0=b 1 0 M L1 L2 L	$R_{rk} = R_{r0} - E_i\left(-\frac{\varrho_1^2}{4at}\right) - E_i\left(-\frac{\varrho_2^2}{4at}\right) - E_i\left(-\frac{\varrho_3^2}{4at}\right) - E_i\left(-\frac{\varrho_4^2}{4at}\right) - E_i\left(-\frac{\varrho_5^2}{4at}\right)$	(1.28)	according to	(1.25)	(according to)	(1.26)

The value R_{r0}, involved in formulae (1,15)-(1,28) represents an outward resistance of the adequate type of the water-pumping construction in an infinite bed; it is determined by the expressions given in table no. 1.

The computation of interference water-pumping constructions (single ones or groups) is made with the use of the same relationships by the method of imposing filtration flows.

In accordance with this, when considering the head function in any point of the bed, the effect of each water-pumping construction on it separately, independent from the other interference water-pumping constructions (as if each of them acted independently) is determined at first. In this way particula head functions $\mathcal{U}_1$, $\mathcal{U}_2$..., are determined.

Then they are summed up algebraically and thus the full head tunction $\mathcal{U}$ is determined.

$$\mathcal{U} = \mathcal{U}_1 + \mathcal{U}_2 + \ldots \qquad (1.29)$$

When individual water-pumping constructions are put into operation at a different period of time or some of them are stopped, the values of head functions are determined by summing up adequate head functions, conditioned by the activity of each newly introduced water-pumping construction; the actual period of time is taken into account, beginning from the moment of putting them into operation. Stopping of the water-pumping construction is taken into account by imposing the head function of the same kind of the water-pumping construction with the same discharge but reverse by its sign.

Let us now dwell upon the procedure of determining "inward resistance" R_{ckb} which as it was mentioned above, must be added to "outward" resistance R_r. R_{r0} and R_{rk} and R_{pp}, see tables Nrs. 1 and 2) in order to define lowering of the level in the well itself.

The inward hydraulic resistance may be defined by the following relationship (Yu. P. Borisov, 1951, V. N. Shchelkachev, 1952) (*).

$$R_{ckb} = 2a\left[ln\frac{r_p}{r_c} + \zeta\left(\frac{l}{m};\ \frac{m}{r_c}\right)\right], \qquad (1.30)$$

where $a = \dfrac{Q}{Q_{tot}}$ (Q is the discharge of the given well, Q_{tot} is the total discharge of the group of interference wells, r_c is the radius of the well),

r_p is the given radius of some conventional "field of effect" of the given well which is defined depending on the outlay of wells. In a plan this conventional "field of effect" may be limited by lines situated in the middle between the adjoining wells,

ζ is a part of hydraulic resistance conditioned by imperfection of the well and defined, depending on the length of the filter l, thickness of the bed and the radius of the well r_c (see, for instance, M. Muscat's works, 1948, I. A. Charny's 1956, N. N. Verigin's 1959 and others).

2. COMPUTATION OF WATER INTAKES ACCORDING TO THE DATA OF TRIAL PUMPINGS

Above mentioned analytical procedures of designing water intake can be applied under known design parameters km and a, and these parameters must be taken as average ones for all part of the water-bearing bed.

(*) When defining R_{ckb} for randomly situated wells (see formula, 1,10 in table 1) the first member in direct brackets is equal to zero, because this part of the resistance is already taken into account by value R_{ro} in this scheme.

When the bed is rather not uniform, the water intake must be computed more precisely according to the results of trial pumpings, carried out during hydrogeological investigations or the exploitation process.

Such a procedure for a steady movement is worked out by A. M. Agadzhanov (1938) and M.E. Altovsky (1940, 1947). It may be also used when the movement of underground waters is unsteady (F. M. Bochever, 1957).

Let us express lowering of the level in the water-pumping construction S in the following general form

$$S = S_{op} + \sum_{i=1}^{n} S_{ip} + \Delta S(t) \tag{11.1}$$

Here S_{op} is lowering conditioned by pumping out from the given well (in which S is determined) with the discharge Q_{op}, S_i is lowering of the level caused by pumping out from i well ($i = 1, 2, \ldots, n$; n — is the number of interference wells besides the regarded well), with discharge Q_{ip}, $\Delta S(t)$ is the additional lowering of the level, occuring with the time and conditioned by gradual general discharge of underground water resources.

In cases when water-pumping constructions are situated near permanent sources of recharge (fir instance, rivers) $\Delta S(t)$ becomes already in a short period of time very small in the equation in comparison with other members and it can be practically ignored when computing.

Then

$$S = S_{op} + \sum_{i=1}^{n} S_{ip} \tag{11.2}$$

Values S_{op}, S_{op} and $\Delta S(t)$ in expressions (11,1) and (11,2) are determined on the basis of experimental data with the help of approximation by these or those empirical relationships.

Thus in order to define S_{op} the results of trial pumpings are usually presented by the "yield curve" $Q_0 = f(S_0)$ which satisfies the equation of the type (fig. 2a)

$$S_0 = a\,Q_0 + b\,Q_0^2 \tag{11.3}$$

or

$$S_0 = c\,Q_0^m \qquad m = 1 \div 2 \tag{11.4}$$

Coefficients a, b, c and m are found out in the usual way on the basis of experimental data. In cases when the unknown value S_{op} is close to the maximum lowering S_0, reached during trial pumpings, it may be defined directly according to the diagram, without using equations (11,3) and (11,4).

$$\sum_{i=1}^{n} S_{ip}$$

as a result of pumping out of interference wells, diagrams $S_i = f_i(Q_i, r_i)$ must be built where r_i is the distance of i well from the well for which the calculation S is done. As a rule, the above mentioned relationships may be presented in a series of straight lines (fig. 2b)

$$S_i = \mathscr{A}_i\,Q_i, \tag{11,5}$$

where A_i is a tangents of the slope angle of the straight lines to the axis Q_i.

At last in order to define the additional lowering of the level with the time $\Delta S(t)$ experimental data over each well are presented by diagrams $S = f(Q_i, t)$ and $S = f(Q_i, lnt)$.

These diagrams may be approximated by different equations, depending on the sizes of water-bearing bed, conditions on its borders and duration of pumpings. For instance, in infinite bed the level with the time changes according to the logarithmical law (fig. 2c and 2d). In this case additional lowering of the level $\Delta S(t)$ may be defined according to the following relationship

$$\Delta S(t) = B_0 \frac{Q_{0p}}{Q_0} \ln \frac{t}{t_0} + \sum_{i=1}^{n} B_i \frac{Q_{ip}}{Q_i} \ln \frac{t}{t_i} \tag{11.6}$$

Here Q_0 and Q_{0p} are discharges of the given well correspondingly when pumping experimentally with duration t_0 and when exploiting during the designed period of time t. Q_i and Q_{0p} are discharges of interference wells when pumping with duration t_i and when exploiting during the period of time given t.

B_0 and B_i are coefficients which characterize the rate of lowering of the levels with discharges Q_0 and Q_i correspondingly during trial pumping. They are defined from the diagrams pointed out as tangents of the slope angles of the straight lines to the axis $\ln t$.

The relationship (11,6) follows directly from the equation (1,10) which is given in table no. 1 for waterpumping constructions in infinite beds.

Really, taking into consideration that when

$$\frac{r^2}{4at} < 0{,}1$$

the function

$$E_i\left(-\frac{r^2}{4at}\right) = -\ln \frac{2{,}25\,at}{r^2},$$

the following formula for a group of interference water pumping constructions can be made up in accordance with (1,29) in order to determine lowering of the level S (N.N. Verigin, 1957, F.M., Bochever and N.N. Verigin, 1961)

$$S = \frac{Q_{0p}}{4\pi Km} \ln \frac{2{,}25\,at}{r_0^2} + \sum_{i=1}^{n} \frac{Q_{ip}}{4\pi Km} \ln \frac{2.25\,at}{r_{0-i}^2} \tag{11.7}$$

Let us distinguish now lowering of the level in the given water-pumping construction for which the definition S is made by the end of trial pumpings t_0 and t_i:

$$S_{0p} = B_0 \frac{Q_{0p}}{Q_0} \ln \frac{2.25\,at_0}{r_0^2}$$

or

$$B_0 \frac{Q_{0p}}{Q_0} \ln \frac{2.25\,a}{r_0^2} = S_{0p} - B_0 \frac{Q_{0p}}{Q_0} \ln t_0 \tag{a}$$

and

$$\sum_{i=1}^{n} S_{ip} = \sum_{i=1}^{n} B_i \frac{Q_{ip}}{Q_i} \ln \frac{2.25\,at}{r_{0-i}^2}$$

$$\sum_{i=1}^{n} B_i \frac{Q_{ip}}{Q_i} \ln \frac{2.25\,a}{r^2_{0-1}} = \sum_{i=1}^{n} S_{ip} - \sum_{i=1}^{n} B_i \frac{Q_{ip}}{Q_i} \ln t_i \qquad \text{(b)}$$

Introducing (a) and (b) into (11,7), we shall receive

$$S = S_{0p} + \sum_{i=1}^{n} S_{ip} + B_0 \frac{Q_{0p}}{Q_0} \ln \frac{t}{t_0} + \sum_{i=1}^{n} B_i \frac{Q_{ip}}{Q_i} \ln \frac{t}{t_i} \qquad (11.8)$$

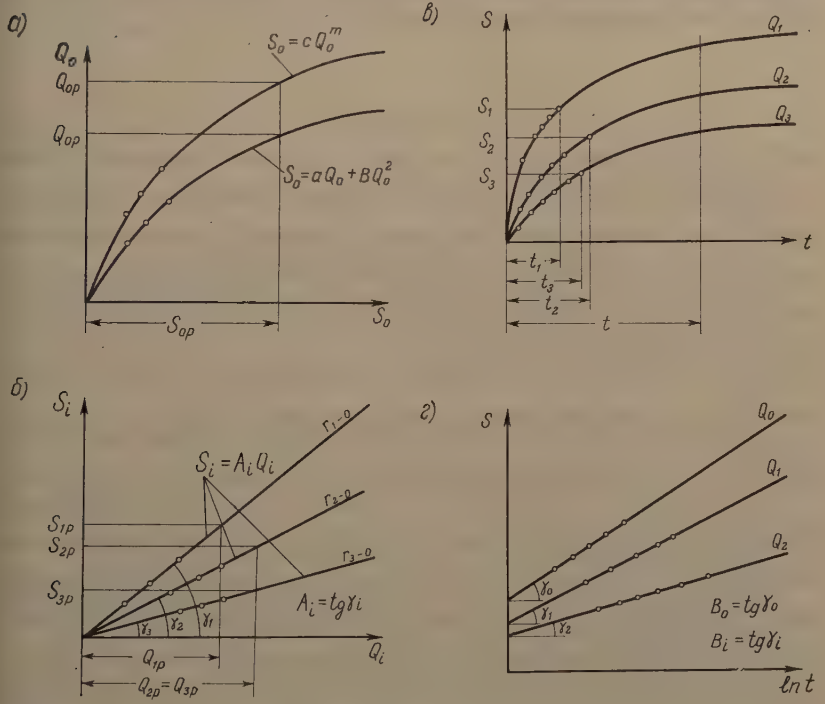


Fig. 2

It is easy to see that the first two members of the right part of this expression satisfy the equation (11,2) and characterize the value of lowering in the given water-pumping construction by the end of trial pumpings. The third and the fourth members, taken together, from the relationship (11,6).

For finite beds the expressions for defining $\Delta S(t)$ can also received from corresponding analytical relationships.

Taking into consideration this circumstance, it can be considered that the proposed procedure of computing water-intake, according to the data of trial pumpings, is theoretically well-grounded.

Alongside with this, as it was already pointed out, under conditions of heterogeneous beds, the utilization of this procedure may produce results more, close to the reality, in comparison with analytical computation.

In particular, under the above mentioned procedures of defining S_{0p} and

$$\sum_{i=1}^{n} S_{ip}$$

directly, according to the experimental data (see formula 11,3)-(II,5), the additionals resistances which are almost always available and are formed near the well at the expense of filter, consolidation of the ground, violation of the linear law of filtration and so on are automatically taken into account.

LITERATURE

Agadzhanov A. M., Raschet debitov vzaimodeystvuyushchikh v artezianskom potoke skvazhin, *Azerb. Neftianoye Khoziastvo*, No. 1, 1938.

Altovsky M.E., Raschet debita po otkachkam iz odinochnykh skvazhin. *Gosgeolizdat*, 1940.

Altovsky M.E., Metodicheskoye rukovodstvo po raschetu vzaimodeistvuyushchikh gruntovykh i arteziankikh vodozaborov. *Gosgeolizdat*, 1947.

Borisov Uu.P., Opredeleniye debita skvazhin pri sovmestnoy rabote neskolkikh ryadov skvazhin, *Trudy Mosk. Neftianogo instituta im. Gubkina*, vyp. II, 1951.

Bochever F.M., O klassifikacii zapasov podzemnykh vod dla vodosnabzheniya, *Sovetskaya geologia*, No. 62, 1957.

Bochever F.M. and Lvova B.N., Opyt otsenki ekspluatatsionnykh zapasov podzemnykh vod dla tseley vodosnabzhenia, *Vodosnabzheniye i santekhnika*, No. 5, 1957.

Bochever F.M., Gidrogeologicheskiye raschety osusheniya pri kariernoy razrabotke mestorozhdeniy poleznykh iskopayemykh, *Razvedka i okhrana nedr*, No. 8, 1959.

Bochever F. M., Tipizatsiya gidrogeologicheskikh uslovii dla tselei rascheta ekspluatatsionnykh zapasov podzemnykh vod dla vodosnabzheniya, *Sovetskaya geologiya*, No. 9, 1958.

Bochever F.M., Priblizhennye gidrogeologicheskye raschety krupnykh vodozaborov i vodoponizitelnykh ustanovok, *Izdaniye VNII VODGEO*, 1961.

Bochever F.M. i Verigin N.N., Metodicheskoye posobiye po raschetam ekspluatatsionnykh zapasov podzemnykh vod dla vodosnabzheniya, *Gosstroyizdat*, 1961.

Verigin N.N., Vzaimodeystviye skvazhin pri zakonturnom zavodneniye neftianykh mestorozhdeniya DAN, t, 91, No. 4, 1953.

Verigin N.N., Ob otsenke proizvoditelnosty vodozabornykh skvazhin c uchetom snizheniya urovnia pri ekspluatatsii, *Vodosnabzheniye i santekhnika*, No. 5, 1957 and No. 3, 1958.

Verigin N.N., O metode rascheta vodoponizheniya s pomoshchyuesovershennykh skvazhin. Trudy Soveshchaniya po voprosam vodoponizheniya, *Gosstroyizdat*, 1959.

Kamensky G.N., Poiski i razvedka podzemnykh vod, Gosgeolizdat, 1947.

Kamensky G.N., Gidrogeologicheskiye issledovaniya i razvedka istochnikov vodosnabzheniya (metodicheskoye rukovodstvo), *Gosgeolizdat*, 1947).

Masket M., Techeniye odnorodnykh zhidkostey v poristoy srede, *Gostoptekhizdat*, 1949.

Pavlovskaya L.N., Filtratsionnye raschety vodoponizitelnykh ustanovok v stroitelnykh kotlovanakh gidrotekhnicheskikh sooruzheniy, *Izvestiya VNIIG im. Vedeneeva*, t. 64, 1960.

Pilatovsky V.P., Vzaimodeystviye krugovykh galerei, dreniruyushchikh plast v usloviyakh uprugogo rezhima, *Inzhenerny sbornik*, AN SSSR, t. XV, 1953.

Pisnukov N.S., Opredeleniye peredvizheniya kontura neftenosnosty i padeniya davleniya pri ekspluatatsii krupnykh mestorozhdeniy. Sb. *Voprosy gidrodinamiki neftianogo plasta*, *Trudy VNII nefti i gaza*, vyp. VI, 1952.

Polubarinova-Kochina P.Ya., Teoriya dvizheniya gruntovykh vod. *Gostekhteorizdat*, 1952.

Charny I.A., Podzemnaya gidromekhanika, *Gostekhizdat*, 1948.

Charny I. A., Metody rascheta neustanovivshegosia pritoka gruntovykh vod k skvazhinam pri glubinnom vodoponishenii, *Inzhenerny sbornik*, AN SSSR, t. XXIII, 1956.

Shestakov V. M., Voprosy rascheta vodoponizitelnykh ustanovok slozhnykh konturov v plane, *Trudy VNII VODGEO*, *Gosstroyizdat*, 1958.

Shestakov V. M., Voprosy rascheta krupnykh vodoponizitelnykh ustanovok, Trudy soveshchaniya po vodoponizheniyu v gidrotekhnicheskom stroitelstve, *VNII VODGEO*, *Gosstroyizdat*, 1959.

Shchelkachev V. N., Osnovnye uravneniya dvizheniya uprugoy zhidkosty v uprugoy poristoy srede. DAN AN SSR, t. 52, No. 2, 1946.

Shchelkachev V. N., Uprugiy rezhim plastovykh vodonapornykh sistem, *Gostoptekhizdat*, 1948.

Shchelkachev V. N., Osobennosty vosstaoovleniya plastovogo davleniya v protsese zakonturnogo zavodneniya, *Neftianoye khoziastvo*, No. 2 and No. 4, 1952.

Shchelkachev V. N., Razrabotka neftevodonosnykh plastov pri uprugom rezhime *Gostoptekhizdat*, 1959.

DEVELOPMENT OF AN INDUSTRIAL GROUND-WATER SUPPLY IN SOUTHERN TURKEY

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Abstract

A new Turkish oil refinery, now under construction near Mersin, Turkey will require approximately 350 cubic meters per hour (about 1500 gallons per minute) of fresh water. The refinery site is two to three kilometers north of the Mediterranean shore and three to four kilometers south of Toros Range foothills. The coastal plain is underlain by about 50 meters of alluvial clay, sand and gravel below which Tertiary marl, limestone and sandstone extend for several hundred meters. Local village and farm water supplies are obtained from dug wells penetrating only a meter or so below the water table, some with lateral tunnels extending from the bottom. Many such supplies are inadequate or fail completely during dry seasons.

Ground-water investigation for the refinery consisted of preliminary geologic reconnaissance, inventory of existing wells, drilling of eight test borings, one of which penetrated 200 meters and the remainder 50 meters, construction of two test production wells and eight observation wells, pumping tests during both wet and dry seasons, and the location and design of four final production wells.

Chief problem was to determine the number and spacing of wells to insure reliable supply during possible prolonged droughts. Local streams dry up each summer. Wells were located to take best advantage of winter recharge from streams and precipitation for balancing dry season pumpage from ground-water storage.

Gravel-packed wells with 12-inch stainless steel screens will produce more than 114 cubic meters per hour (500 gallons per minute) without danger of salt-water contamination from nearby shore.

Résumé

Une nouvelle raffinerie de pétrole en construction près de Mersin, Turquie, aura besoin d'environ 350 mètres-cube d'eau douce par heure (à peu près 1500 gallons par minute). L'emplacement de la raffinerie est à 2 ou 3 kilomètres au nord de la Méditerranée et à 3 ou 4 kilomètres au sud des contreforts du Taurus. La plaine côtière est située sur une couche d'environ 50 mètres d'argile alluvionnaire, sable et gravier, au-dessous de laquelle la marne Tertiaire, le calcaire et le grès descendent à une profondeur de plusieurs centaines de mètres. L'approvisionnement en eau des villages et des fermes se fait par des puits pénétrant jusqu'à environ un mètre au-dessous du niveau des eaux. Certains puits sont munis de tunnels latéraux embranchés du fond. Plusieurs de ces sources sont insuffisantes ou à sec en saison sèche.

Les recherches d'eau souterraine pour la raffinerie ont consisté en reconnaissances géologiques, d'une liste des puits existants, de huit forages expérimentaux, l'un d'eux ayant pénétré jusqu'à 200 mètres, les autres — jusqu'à 50 mètres, de construction de deux puits d'essai pour production et de 8 puits d'observation avec des essais de pompage pendant la saison de pluie et la saison sèche, et de l'emplacement et de la forme de 4 puits définitifs pour la production.

Le problème principal consistait à déterminer le nombre des puits et leur distance pour s'assurer d'un approvisionnement en eau certain pendant des saisons sèches prolongées. Les cours d'eau locaux se dessèchent chaque été. Les puits furent emplacés pour tirer avantage en hiver d'un remplissage dû aux cours d'eau et aux pluies, qui compenserait le pompage des réserves souterraines pendant la saison sèche.

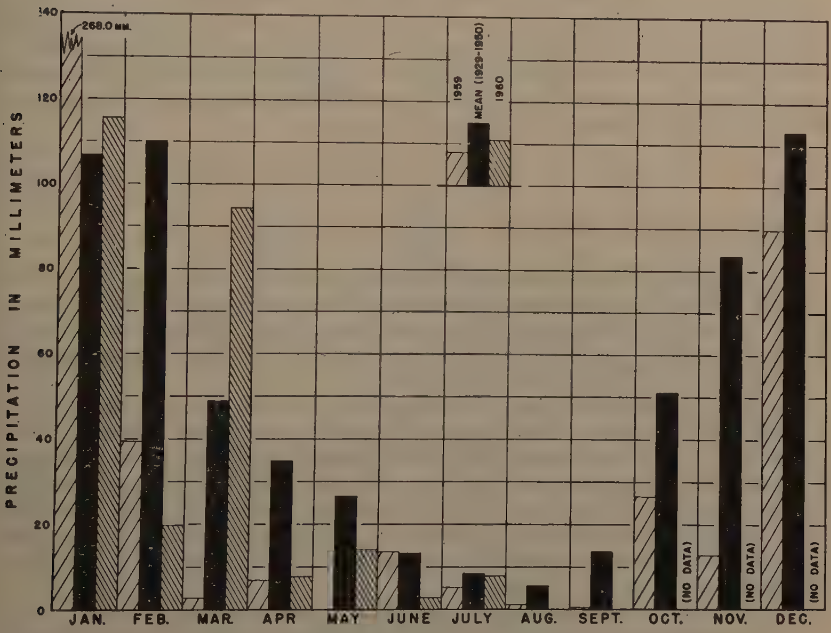
Les puits remplis de gravier et munis de tamis de 12 pouces en acier inoxydable produiront plus de 114 mètres-cube par heure (500 gallons par minute) sans danger de contamination par l'eau salée de la côte voisine.

1. Introduction

A new Turkish oil refining company, Anadolu Tasfiyehanesi Anonim Sirketi, has nearly completed the construction of a large refinery near the seaport of Mersin, on the Mediterranean Coast of Turkey. Mobil International Oil Company of the United States, The British Petroleum Company, Ltd. of Great Britain, and Shell International Petroleum Company, Ltd. of Holland have formed the Turkish company. When in operation, the refinery will require a continuous supply of 350 cubic meters per hour (1500 gallons per minute) of fresh water.

The refinery is situated on the alluvial plain of the Deli çay, a river having a relatively small watershed with headwaters in the Toros Mountains. In this locality, the coastal plain is narrow; the distance between the foothills of the mountains and the shore is six to seven kilometers. The refinery is two to three kilometers from the shore.

At this site, the land surface has a smooth slope rising gently inland toward the mountains. The refinery property is mostly less than 15 meters above sea level. The channel of the Deli çay River has cut two to three meters below the flood plain level. Numerous irrigation canals traverse the area.



PRECIPITATION AT MERSIN, TURKEY

Fig. 1

During the winter months, heavy rains and snows occur in the mountainous part of the Deli çay watershed. Occasionally, there is some minor flooding of the lowland, as in January 1959. On the other hand, the summer months are usually very dry. From about May to October, the flow of the Deli çay River disappears underground at the north edge of the coastal plain, and reappears as surface flow about one kilometer from the sea. Figure 1 shows the monthly precipitation at Mersin for the period 1929-1950.

2. GEOLOGY AND HYDROLOGY

The alluvial plain in the refinery area is composed of interfingering layers of clay, sand, gravel and boulders of Quaternary age. Some of the coarser deposits have been cemented to form conglomerate. The alluvium is genetically related to the present position of the Deli çay River because the sediments are much coarser and thicker near the river than they are to either side. The thickness of the alluvium ranges from about 50 meters along the river to 10 meters or less in some places only three or four kilometers to either side of the river.

Near the Toros foothills, the surface is formed by caliche beds of Pliocene age, which are underlain by Miocene limestone and marl beds containing layers of sandstone and conglomerate. The Miocene formations dip southward toward the sea and are at least several hundred meters thick where they underlie the alluvium at the refinery site.

Both the alluvium and the Miocene rocks are water bearing but the alluvium is by far the more permeable. Wells penetrating 200 meters or so of the Miocene rocks encounter artesian conditions, chiefly in the conglomerate and sandstone layers. However, the yield from these layers is not large and the water is likely to be high in hardness and may contain considerable iron and hydrogen sulfide gas. The recharge area for the Miocene aquifers lies in the Toros foothills where they are exposed in a broad belt paralleling the main mountain system.

3. GROUND-WATER INVESTIGATIONS

A preliminary field inspection of the refinery area was made early in 1959. At the start of this work, topographic maps and all available geologic maps and reports for the area were obtained from the Mineral Research and Exploration Institute of Turkey. In addition, the records of ten test wells, drilled by a Turkish governmental water agency in 1957 were obtained for study.

A visit was made to all the small villages on the coastal plain near the Deli çay River and to the owners of local irrigation wells. Information was obtained about the depth and capacity of the wells, the kind of sediments encountered and the seasonal changes in water level. Almost all such wells were dug by hand, many having tunnels extending horizontally from the bottom, a meter or so below the dryseason water table. The seasonal fluctuation of ground-water level is most pronounced along the Deli çay River, where even during the last year and a half, the depth to the water table has changed nearly 10 meters.

The geologic reports and the field inspection indicated the following :

1. The alluvium contains sand and gravel layers of moderate to high permeability.

2. Most of the village and irrigation wells penetrate only the top part of the saturated sands and gravels.

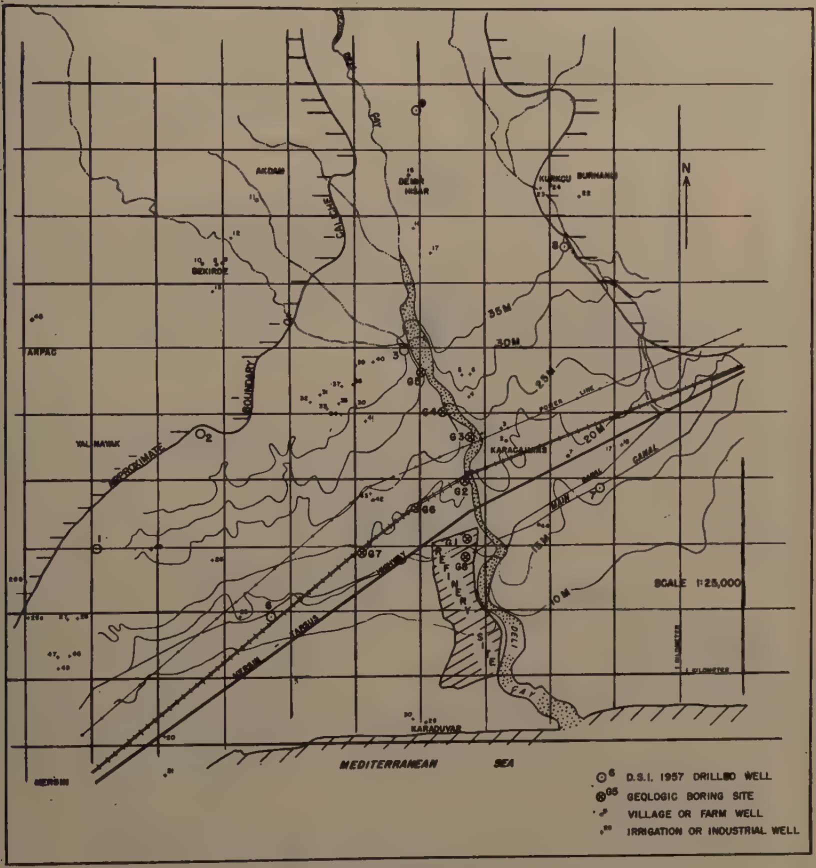
3. The natural seasonal range in ground-water level is large, especially near the river. This is the reason why many of the village wells go dry in the summer, rather than because of excessive withdrawal of water.

4. When there is flow in the river during the winter and spring months, large quantities of water infiltrate through the river bed into the underlying sands and gravels. This recharge is, of course, greatest near the river, but all of the coastal plain receives some recharge from winter and spring rains.

5. The chemical quality of the water in the alluvium is generally better than water in the deeper Miocene aquifers.

3.1. *Test Borings*

When the field inspection had been completed, locations were selected for drilling eight test borings. Two of these were inside the refinery property, four were along the river toward the foothills, and two were away from the river as shown in figure 2. One of the borings in the refinery property was drilled to a depth of 200 meters in order to obtain information about the Miocene sediments underlying the alluvium. All other borings were drilled specifically for testing the alluvium and were terminated when conglomerate was encountered. These alluvial borings were from 40 to 50 meters deep. When drilling was completed, slotted casing was installed so that measurements could be made of later changes in water level.

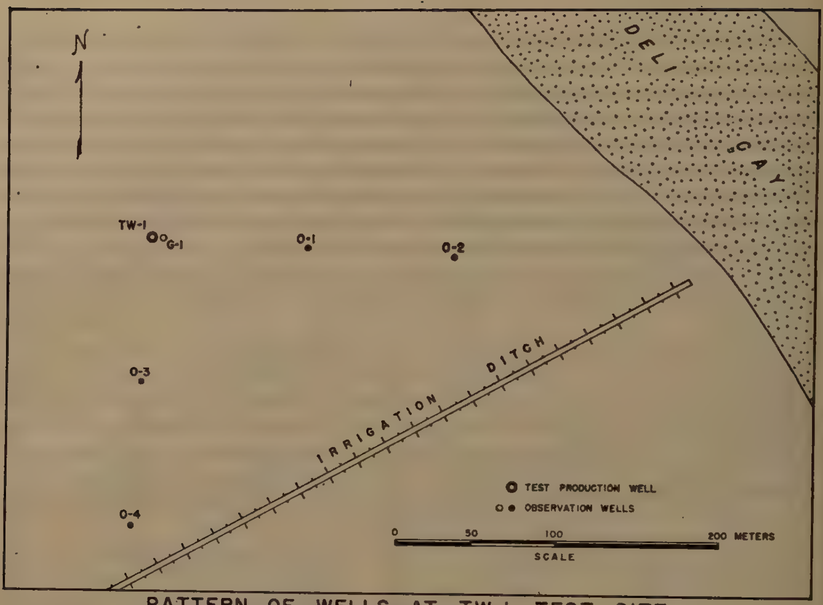


MAP OF REFINERY AREA SHOWING GEOLOGIC BORING SITES
NEAR MERSIN, TURKEY

Fig. 2

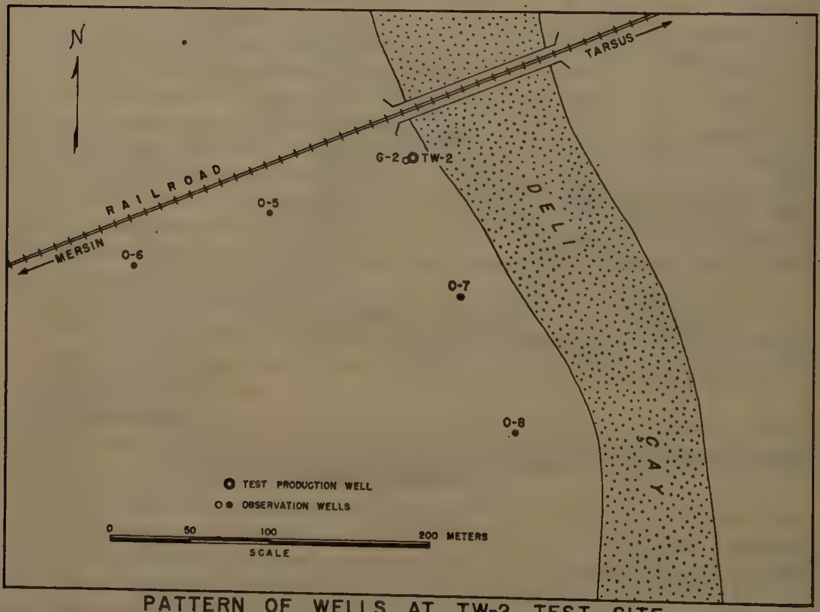
3.2. *Test Production Wells*

The results of the borings were analyzed and test production wells were constructed at two of the boring sites. These wells are 12 inches in diameter and have



PATTERN OF WELLS AT TW-1 TEST SITE

Fig. 3



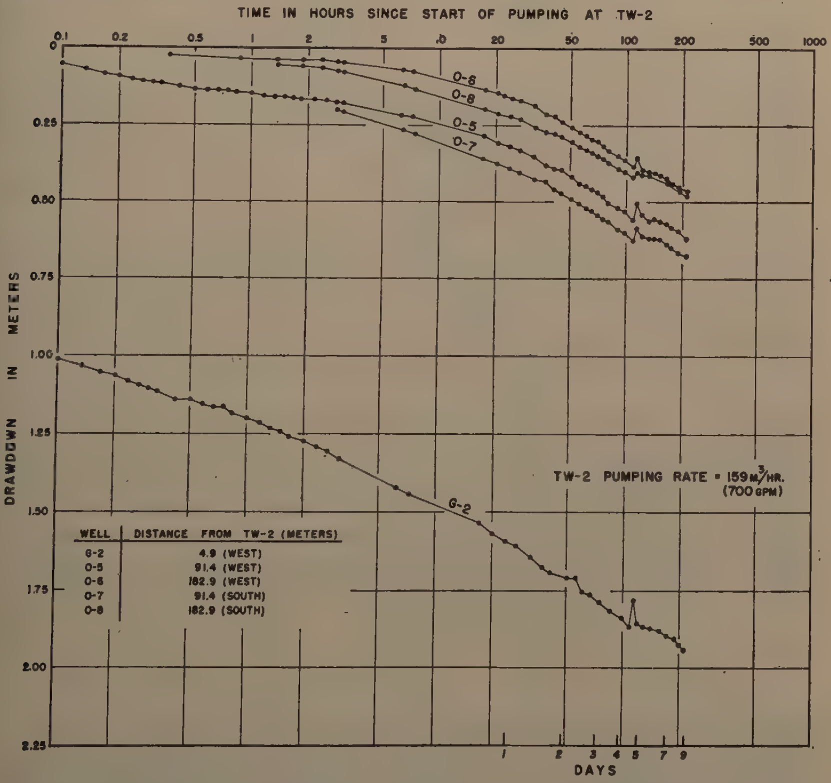
PATTERN OF WELLS AT TW-2 TEST SITE

Fig. 4

a gravel pack around the slotted casing. The first production well was drilled about 250 meters from the river bank and the second only 10 meters from the river bank. Four small diameter observation wells were drilled at each production well site so that the decline of water level during pumping tests could be measured in directions both parallel and perpendicular to the river. All of these wells were about 50 meters deep and screened with perforated casing. The locations of the observation wells in relation to the pumping well and the Deli çay River at each test site are shown in figures 3 and 4.

3.3. *Pumping Tests*

Each of the two test production wells was pumped at a constant rate of 159 cubic meters per hour (700 gpm) for several days. During each period of pumping, the drawdown in the pumping well and nearby observation wells was accurately measured. These data for the first test are shown in figure 5, in which the drawdown is given on the vertical scale and the time since the start of pumping is shown on the logarithmic horizontal scale.



DRAWDOWN EFFECTS DURING THE PUMPING TEST AT WELL TW-2 NEAR MERSIN, TURKEY OCTOBER — NOVEMBER, 1959

Fig. 5

There were several objectives in performing the pumping tests. These included:

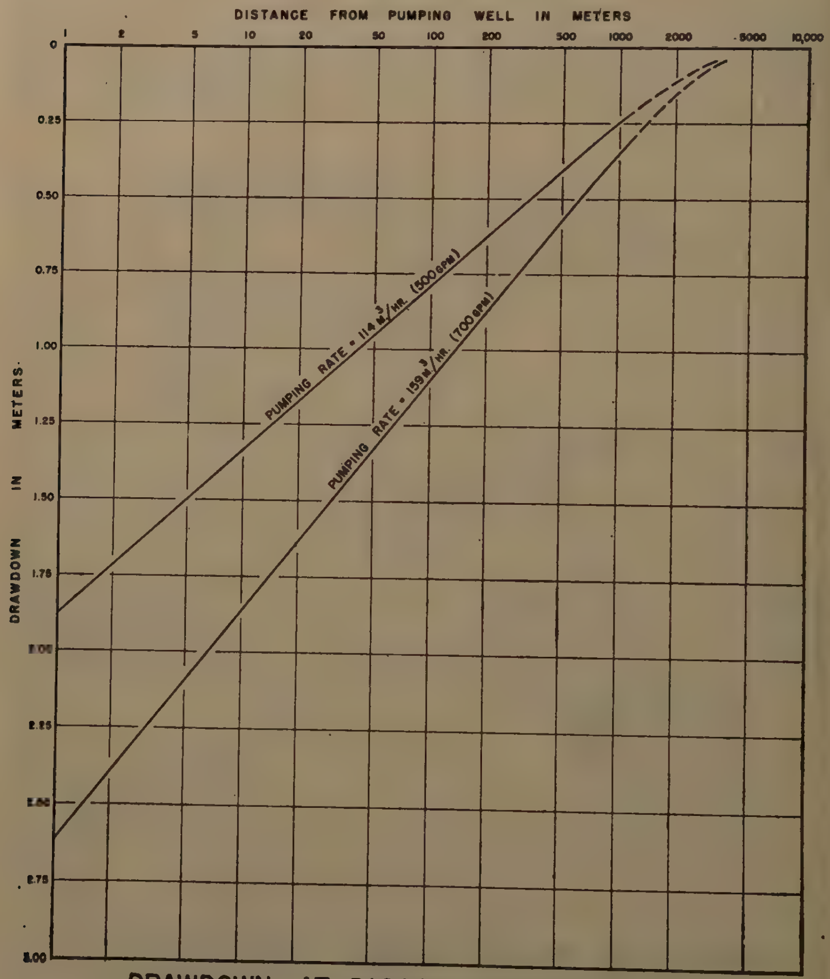
1. Determination of the capacity of a modern type of well that completely penetrates the alluvial aquifer.

2. Determination of the probable drawdown in the permanent wells when producing a given quantity of water.

3. Determination of the period of time that wells could continue to pump a given quantity of water, even if there should be no recharge.

4. Determination of the hydraulic relationship between the aquifer and the Deli çay River.

5. Determination of the amount of interference to be expected between wells spaced certain distances apart, and pumping at various rates.



DRAWDOWN AT DISTANCE FROM A WELL PUMPING FOR 6 MONTHS WITHOUT RECHARGE

Fig. 6

The pumping tests provided considerable information on all of the above factors. After the data were analyzed, it was then possible to select sites for the appropriate number and spacing of wells needed to develop 350 cubic meters of water per hour, with reasonable assurance that this supply would be available throughout prolonged drought periods, and year after year. For example, the drawdown data obtained during the pumping tests were used to construct the graphs shown in figure 6 that indicate how much drawdown can be expected to occur at various distances from a well pumping either 114 cubic meters per hour (500 gpm) or 159 cubic meters per hour (700 gpm) at the end of a six-month drought. That is to say, the graphs apply to the conditions that would exist if all of the water pumped were derived from groundwater storage. Figure 6 indicates that a refinery well, pumping 159 cubic meters per hour continuously for six months without recharge, would produce a decline of water level of about three-fourths of a meter at a distance of 300 meters from the pumping well.

With the aid of such graphs, several hypothetical combinations of well yields and well spacings were considered in selecting a final pattern of new wells. Certain economic factors were also considered. For example, it is not practicable to space wells so far apart that all interference is avoided, because the cost of connecting pipelines would be excessive. Neither is it practicable to space wells so close together that the well screens might be dewatered because of excessive interference.

The boring records showed that throughout the refinery area, the top of a highly permeable layer of sand and gravel occurs about 15 meters below the land surface. This zone receives the most direct recharge from the Deli çay River and from infiltration of rainfall in the local area. For this reason, it was considered desirable to install screens opposite this shallow zone in all the new wells.

The four permanent production wells were located about 300 meters apart along a line parallel to the river and approximately 15 meters from the west bank. The test data indicate that with this pattern, these wells will be capable of a total yield of more than 450 cubic meters per hour at the end of a prolonged dry season; they are situated to take maximum advantage of winter and spring recharge from the Deli çay River; the pumping level in the wells will be moderate; and the interference between wells will be small. Figure 7 shows the construction features of one of the production wells.

It should be recognized that such pumping tests are not precise in predetermining the individual performance of wells after they are put into service. The data obtained from a pumping test represents an average of all the hydrologic conditions within the area that was affected during the test. Therefore, when a new well is constructed some distance away from the site of a test well, its performance may be somewhat better or somewhat poorer than was estimated from the preceding pumping test data. For this reason, pilot holes were drilled at each site chosen for a permanent production well, to guard against the chance selection of a poor site.

3.4. *Chemical Quality of the Ground Water*

Because the refinery is near the Mediterranean shore, care had to be taken so that salty water will not move into the well field from the sea, and so that highly mineralized water will not rise vertically from deep zones in the Miocene formations. The test data indicate that water levels in the well field will not be drawn down below sea level and that a hydraulic divide will be maintained between the well field and the sea. This divide will be in the form of a low mound of ground water, beneath which the hydrostatic head will be greater than in the well field or at the shore. Under such conditions, there can be no movement of sea water from the shore to the well field.

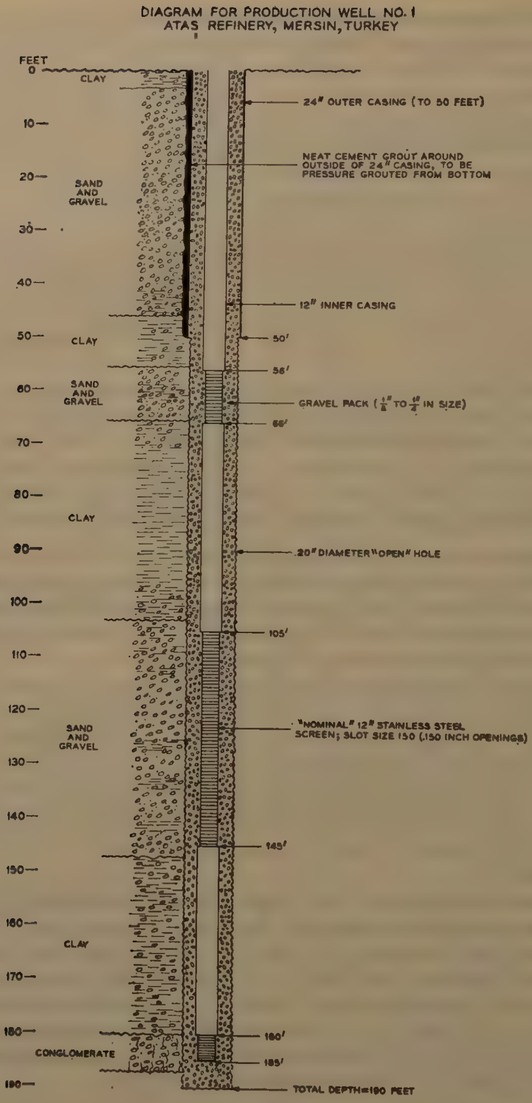


DIAGRAM FOR PRODUCTION WELL NO. 1
ATAS REFINERY, MERSIN, TURKEY
FEET
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
CLAY
SAND AND GRAVEL
CLAY
SAND AND GRAVEL
CLAY
SAND AND GRAVEL
CLAY
CONGLOMERATE
24" OUTER CASING (TO 50 FEET)
NEAT CEMENT GROUT AROUND OUTSIDE OF 24" CASING, TO BE PRESSURE GROUTED FROM BOTTOM
12" INNER CASING
50'
56'
GRAVEL PACK (1/8" TO 1/4" IN SIZE)
66'
20" DIAMETER "OPEN" HOLE
105'
"NOMINAL" 12" STAINLESS STEEL SCREEN; SLOT SIZE 150 (.150 INCH OPENINGS)
145'
180'
185'
TOTAL DEPTH=190 FEET

Fig. 7

4. SUMMARY

The refinery well field consists of four 12-inch gravel-packed wells, each designed to produce about 115 cubic meters per hour. The wells average about 50 meters in depth and completely penetrate an alluvial aquifer composed of numerous interconnected sand and gravel layers. The wells are 300 meters apart, along a line parallel to the Deli çay River, and are 15 to 20 meters from the river bank.

In the area of the refinery, the Deli çay River flows during the winter and spring months but dries up completely during the summer months. The river bed is broad and composed mostly of coarse gravel and boulders. When there is flow in the river, large quantities of water infiltrate through the river bed and recharge the alluvial aquifer, in which the water level is generally several meters below the river bed. The wells were located to take advantage not only of the more permeable conditions in the aquifer near the river, but also to better utilize the winter and spring recharge from the river.

Pumping-test data obtained at two localities were used to calculate the most effective spacing of wells, and as an aid in the design of well construction. The wells are spaced and designed in such a way that full use is made of the shallowest water-bearing sand and gravel layer.

During each dry season, nearly all of the water pumped will come from ground-water storage, and the local water level will decline throughout such periods. However, winter and spring rains, plus a large amount of infiltration from the Deli çay River will contribute more recharge to the alluvial aquifer than will be pumped during wet seasons. The net result is that the well field will utilize the alluvial formation as if it were a surface reservoir with intermittent input. It has been calculated, on the basis of the test data, that the annual recharge to the local ground-water reservoir is considerably in excess of the proposed annual pumpage. The refinery wells will intercept only a part of the fresh ground water that is moving through the alluvial aquifer to zones of escape at or near the shore. Therefore, even though water levels may decline considerably during each dry season, they will rise again during the next wet season. There will be no continuing decline of water levels from year to year.

NOTE SUR QUELQUES MÉTHODES D'ESTIMATION DES RESSOURCES EN EAUX SOUTERRAINES EMPLOYÉES EN TUNISIE

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RÉSUMÉ

On expose succinctement les méthodes utilisées pour établir le bilan hydrologique des nappes souterraines en s'appuyant sur quelques exemples portant sur :

- des nappes alluvionnaires
- des nappes de formations sableuses
- des nappes de formations calcaires

On donne quelques résultats acquis concernant l'alimentation des nappes, leurs réserves et le mode d'exploitation.

Note about the underground water ressources in Tunisia

ABSTRACT

This note give some informations about the methodes used for evaluation of the hydrologic, balance of the underground formations, taking some examples concerning Dune, sand, and limestone formations.

Some results have been obtained for the evaluation of yield, the size of the reserves and the best ways of developpement.

Lors de l'établissement du bilan dynamique des eaux souterraines de grands ensembles, les méthodes classiques, basées sur la connaissance des caractéristiques hydrodynamiques de la nappe étudiée au moyen de forages et d'essais de pompage sont, en règle générale, celles qui donnent les résultats les plus précis. Elles ont, toutefois, l'inconvénient d'être longues, onéreuses et de ne pouvoir s'adapter facilement à certaines formations géologiques telles que calcaires, sables dunaires.

Pour ces dernières formations, l'étude des débits des cours d'eau et des sources, en période d'étiage, peut permettre d'établir des bilans approchés, à condition de connaître parfaitement la géologie et la tectonique de la région.

Cette note présente quatre études de bilan hydrogéologique effectuées en Tunisie depuis 1957:

— Nappes de formations alluvionnaires : Estimation des ressources dynamiques par essais de pompage.

Exemple : Étude du Bled Sisseb.

— Nappes dans les formations perméables en grand: Estimation des ressources dynamiques par l'étude des courbes de tarissement.

Exemple: I Bassin dans le Flysch Oligocène (Oued Zerga).
II Bassin dans les calcaires Campanien et Éocène (Oued Maden).

— Nappes de formations dunaires : Estimation des ressources dynamiques par jaugeages différentiels.

— Exemple : Dunes des Nefzas.

1. NAPPES DE FORMATIONS ALLUVIONNAIRES — ESTIMATION DES RESSOURCES DYNAMIQUES PAR ESSAIS DE POMPAGE.

La plupart des grandes plaines du Centre et du Nord de la Tunisie sont des plaines d'effondrement à sédimentation rythmée : argiles, argiles sableuses, sables, galets et graviers. Dans le cas particulier de l'établissement du bilan des eaux souterraines contenues dans les alluvions de ces plaines, les méthodes d'étude purement hydrogéologiques sont d'un emploi particulièrement approprié.

1. 1. *Méthode d'Ètude.*

Afin de déterminer de façon aussi précise que possible les ressources dynamiques de la nappe il est nécessaire d'étudier dans une première phase :

— les terrains dans lesquels elle circule

— la direction et la pente de l'écoulement

— les caractéristiques hydrodynamiques telles que perméabilité, transmissivité, coefficient de restitution, porosité utile...

Ce n'est qu'au terme de cette première phase d'étude qu'il devient possible de définir le débit récupérable, d'implanter les captages nécessaires, de déterminer leurs caractéristiques probables.

Les diverses études mentionnées ci-dessus ne peuvent se faire qu'au moyen de forages et d'essais de pompage.

1. 1.1. *Exécution de forages*

— *Implantation des forages*

L'implantation des forages doit tenir compte de tous les documents existants, notamment ceux relatifs aux puits de surface, l'expérience prouvant que dans ces grands ensembles sédimentaires la direction d'écoulement des nappes profondes est en général la même que celle de la nappe phréatique.

Les forages sont implantés, si possible, le long d'une ligne isopiézométrique, la pente de l'écoulement étant déterminée grâce à quelques piézomètres situés perpendiculairement à cette ligne d'étude.

— *Etude Géologique des Forages*

Des cuttings doivent être prélevés tous les mètres de façon à permettre l'obtention d'une bonne coupe lithologique, et lorsque cela paraît nécessaire la détermination de l'âge du sédiment par l'étude de la microfaune. Le carottage mécanique peut également être utile, notamment pour déterminer la granulométrie de certains horizons.

Enfin le carottage électrique permet de déceler tous les niveaux perméables.

1. 1.2. *Essais des Forages*

— *Essais provisoires à trou libre*

Compte tenu de tous les renseignements fournis par l'étude géologique du forage, on exécute alors dans chacun des horizons perméables reconnus dans le forage étudié un essai de pompage à trou libre.

Cet essai permet non seulement de se faire une idée, très approximative, des caractéristiques de l'horizon essayé, mais également de prélever un échantillon représentatif de l'eau de la nappe, de déterminer son niveau statique et d'étudier la granulométrie des sédiments remontés au cours du pompage.

Lorsque tous les horizons sont essayés on transforme le sondage soit en point de mesures en plaçant un piézomètre dans chacune des formations intéressantes, soit en captage d'exploitation si la chose s'avère utile pour l'étude de la nappe ou pour son exploitation future.

(Il peut être, quelquefois, intéressant de capter un deuxième horizon aquifère par un forage jumeau).

— *Essais de Courte Durée*

Lorsque le forage est capté, on procède à des essais de pompage de courte durée (12 à 24 h en général). Ces essais correspondent aux habituels essais de réception d'un forage. Les seules mesures faites le sont dans le forage pompé lui-même :

Mesure du rabattement apparemment stabilisé pour un certain nombre de débits, mesure de la remontée du plan d'eau à la fin du pompage. De tels essais ne peuvent donner qu'une valeur très approchée du coefficient de transmissivité et uniquement pour une zone restreinte située autour de la crépine. Néanmoins, ils permettent de déceler l'influence de pertes de charge singulières.

— *Essais de Longue Durée*

Afin de vérifier et d'étalonner l'ensemble des résultats fournis par les essais provisoires, il est nécessaire de procéder à des essais de pompage de longue durée sur un certain nombre de forages choisis en fonction des impératifs de l'étude. Un réseau de piézomètres doit alors être installé autour de chacun d'eux. Ces essais peuvent avoir une durée allant de plusieurs jours à plusieurs semaines si les conditions locales le demandent. Leur dépouillement, par la méthode de non equilibre, permet le calcul des coefficients de transmissivité et de restitution représentatifs d'une vaste zone centrée sur le sondage essayé.

Il est évident que de tels essais sont d'un coût particulièrement élevé et qu'ils doivent être limités aux exigences de l'étude.

1. 2. *Exemple d'Application — Etude du Bled Sisseb*

1. 2.1. *Environnement Géologique du Bled Sisseb*

Le bled Sisseb * constitue la partie Nord de la plaine effondrée et subsidente de Kairouan. Les alluvions quaternaires de la plaine se raccordent de toutes parts, sauf vers le Sud où elles se prolongent en direction de Kairouan, aux plis de bordure par des failles ou des systèmes de failles en gradins. (cf figure 1).

L'alimentation des nappes de la plaine provient :

— d'infiltrations directes d'eaux météroriques

— d'infiltrations des eaux d'étiage ou de crues des principaux oueds, notamment des oueds Nebaana, Ketem, Krioua, dans leurs alluvions actuelles ou anciennes.

— du déversement des nappes contenues dans le synclinal gréseux, d'âge Oligo-Miocène de Saouaf-Oued Saadine.

Ce synclinal effondré est recouvert en transgression par des dépôts alluvionnaires.

La sédimentation du Bled Sisseb, s'explique par la divagation des principaux oueds au cours de l'histoire géologique et par l'extention des cônes de déjection dus à l'érosion des reliefs voisins. Ce mode de dépôt entraîne un développement lenticulaire des horizons et permet aux diverses nappes de communiquer entre elles. Dans

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(*) Cette étude a été réalisée de 1956 à 1959, à la demande du Groupe de l'Hydraulique et des Aménagements Ruraux du Secrétariat d'État à l'Agriculture de la République Tunisienne par la Société Grenobloise d'Études et d'Applications Hydrauliques. Depuis 1960 les nouveaux travaux hydrogéologiques entrepris sont exécutés par la Société Centrale Pour l'Équipement du Territoire.

la zone d'alimentation il n'existe qu'un seul système aquifère qui se diversifie vers l'aval où il est alors possible de distinguer deux ensembles :

— la partie supérieure du remplissage, siège de la nappe phréatique,

— la partie profonde, plus grossière, plus perméable dans laquelle les divers horizons aquifères sont en relation assez étroite.

Ces deux ensembles sont séparés par une cinquantaine de mètres d'argiles peu sableuses qui constituent un bon obstacle à leur communication.

1. 2.2. *Résultats de l'Ètude*

— *Comportement des Nappes*

L'écoulement se fait en règle générale selon une direction Nord Ouest — Sud Est. Toutefois des conditions hydrogéologiques locales peuvent modifier cette direction (alimentation par l'oued Nebaana par exemple). La pente piézométrique moyenne de l'écoulement de la nappe profonde et voisine de 1/1.000, tandis qu'elle est en moyenne de 2/1.000 dans le cas de la nappe phréatique.

Cette dernière valeur peut d'ailleurs être localement beaucoup plus importante. (6 à 10/1.000 dans la zone d'alimentation de l'oued Nebaana par exemple).

Dans toute la région étudiée par forage (cf figure 1), la nappe profonde est une nappe en charge, la nappe phréatique peut également être localement en charge sous un horizon argileux pouvant atteindre 10 m de puissance. La différence de charge entre nappes profonde et phréatique croît dans le sens de l'écoulement. Les études qui se poursuivent actuellement dans la zone d'alimentation (synclinal de Saouaf — Oued Saadine) permettront de préciser d'avantage ce schéma.

— *Débit des Nappes*

Le tableau ci-dessous résume les caractéristiques des divers forages effectués :

Noms.	X_g	Y_g	Z_m	NS_m	Prof. crépine (m)	Résidu sec (mg/1)	Perméabilité m/s
B. S. II	8.62.12	40.00.25	73,27	54,45	110—145	1120	10^{-4}
B. S. III	8.64.50	39.96.40	61,80	53,41	96—158	1240	6. 10^{-5}
B. S. IV	8.67.50	39.94.00	55,21	50,95	138—173	1260	9. 10^{-5}
B. S. V	8.63.10	39.98.80	66,20	52,44	108—145	1000	4. 10^{-5}
B. S. VI	8.63.68	39.94.65	63,39	52,45	132—160	1140	2. 10^{-5}
B. S. A	8.66.30	40.01.70	66,25	54,46	100—151	940	9. 10^{-5}
B. S. B	8.61.80	40.04.40	79,00	57,70	133—166	1240	2,5 10^{-4}
B. S. B'	id.	id.	79,00	56,79	56— 95	820	3 10^{-4}
B. S. C	8.58.80	39.98.30	84,20	54,80	32— 55		2 10^{-4}
B. S. E	8.60.20	39.99.40	78,00	54,20	95—115	1240	9. 10^{-5}
B. S. I	8.77.30	40.03.95	45,00	44,20	49— 65	1000	2 10^{-4}

Les valeurs du coefficient de perméabilité consignées danstce tableau sont deduites d'essais provisoires. Afin de les étalonner et vérifier, quatre essais de pompage de longue durée ont eu lieu, un cinquième est en cours (Forage Bled Sisseb I).

Ces essais ont intéressé les forages Bled Sisseb II, IV, B et B'. Ils ont nécessité le forage de 10 piézomètres.

Ils conduisent à des valeurs du coefficient de perméabilité plus importantes. Le tableau ci-dessous résume, par exemple, les résultats déduits de l'essai qui a eu lieu dans le forage Bled Sisseb B'.

Point de mesures	Transmissivité : T (m2/s)		K (m/s)
	Rabattement	Remontée	
Piézomètre Z_2	2,5 10^{-2}	2,2 10^{-2}	6. 10^{-4}
Piézomètre Z_4	2,6 10^{-2}	2,3 10^{-2}	6. 10^{-4}
Bled Sisseb A	3,3 10^{-2}	1,7 10^{-2}	4 à 7. 10^{-4}

La transmissivité moyenne de l'horizon aquifère profond est, d'après l'ensemble des essais, voisine de 2. 10^{-2} m^2/s.

Compte tenu des divers renseignements obtenus, le débit global des nappes du Bled Sisseb a pu être évalué à 10.000.000 m^3/an, le débit de la nappe phréatique entrant dans ce chiffre pour environ 2.000.000 m^3/an.

Cette estimation pourra être précisée davantage par les travaux en cours, mais représente vraisemblablement un bon ordre de grandeur. Les travaux en cours ont également pour but de déterminer de façon aussi exacte que possible les réserves statiques des nappes du Bled Sisseb. En l'état actuel de nos connaissances celles-ci s'élèveraient à environ 250.000.000 m^3 pour une baisse du niveau des nappes égales à 52 m.

2. Nappes dans des formations perméables en grand — Estimation des ressources dynamiques par l'etude des courbes de tarissement.

Dans le cadre de l'étude hydrologique de la Tunisie septentrionale, certains bassins versants types, sont soumis à des relevés hydrométriques systématiques.

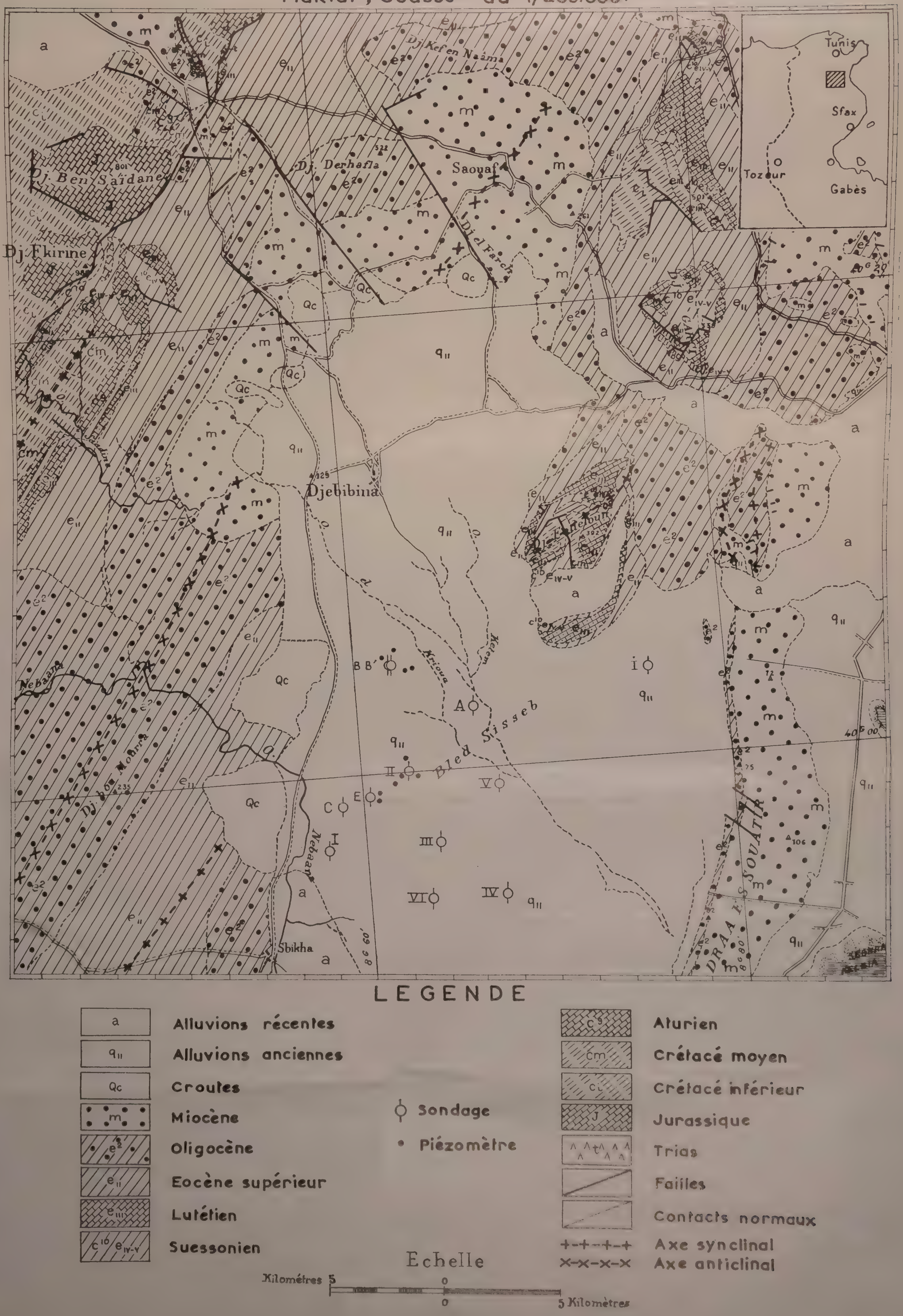
A partir des résultats de la première année de mesures (1^{er} Septembre 1959 — 31 Août 1960), nous avons tenté d'établir, outre le bilan des eaux de surface, le bilan des eaux souterraines de quelques bassins, dont nous avions déterminé par ailleurs la géologie et la tectonique. Il s'agit en particulier, de l'oued Zerga drainant des séries marno-gréseuses du Flysch Oligocène, et de l'oued Maden drainant des massifs calcaires campaniens et éocénes.

2. 1. *Méthode d'Etude*

La méthode d'étude employée consiste à établir le bilan de tous les exutoires d'une formation aquifère. On se place pour cela dans les conditions les plus simples : celles de l'étiage. La saison sèche en Tunisie ayant au minimum cinq mois, la durée de la période d'étiage excède largement le temps de ressuyage hypodermique et les oueds

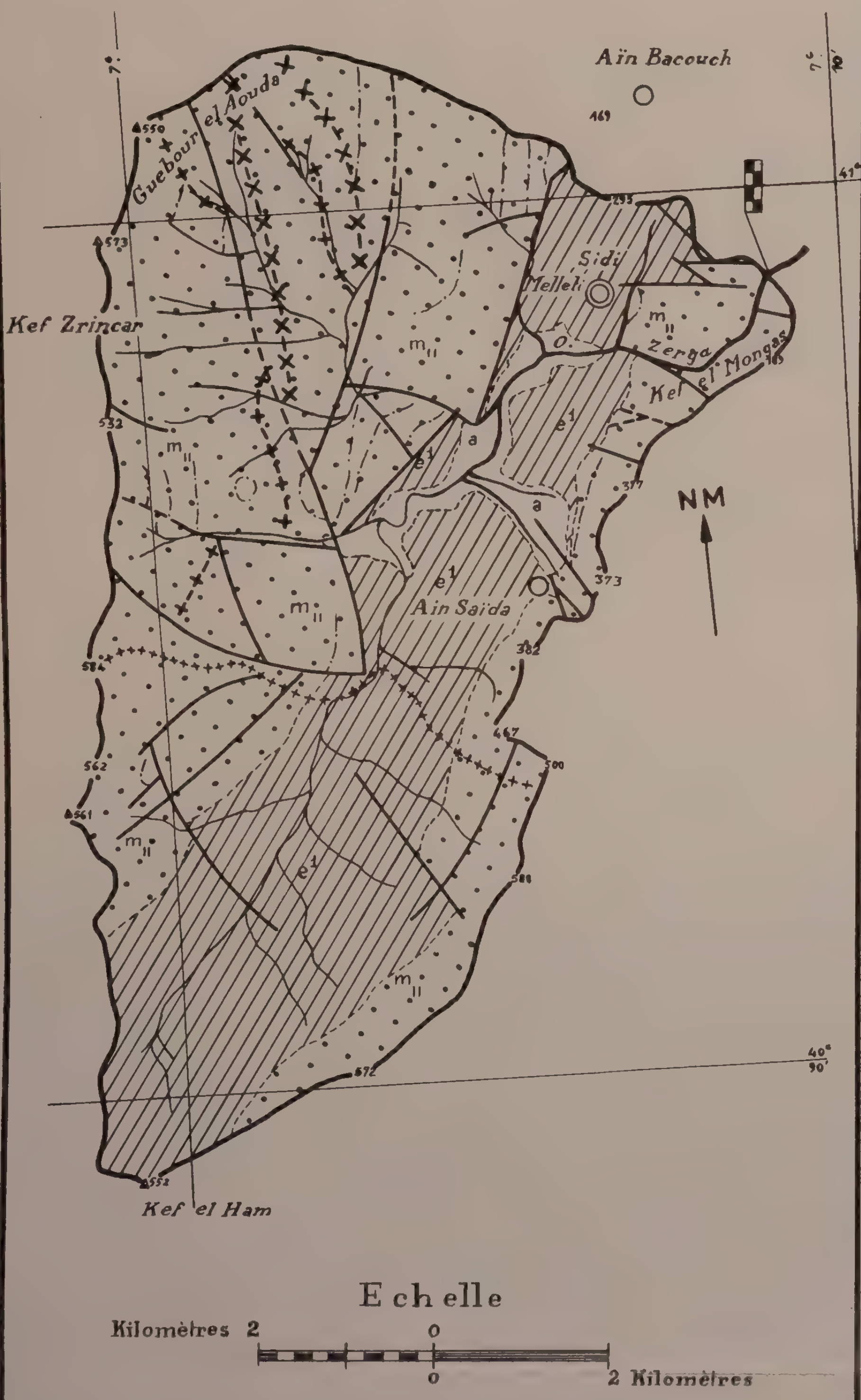
BLED SISSEB

Extrait des cartes géologiques provisoires
Maktar, Sousse au 1/200.000^e



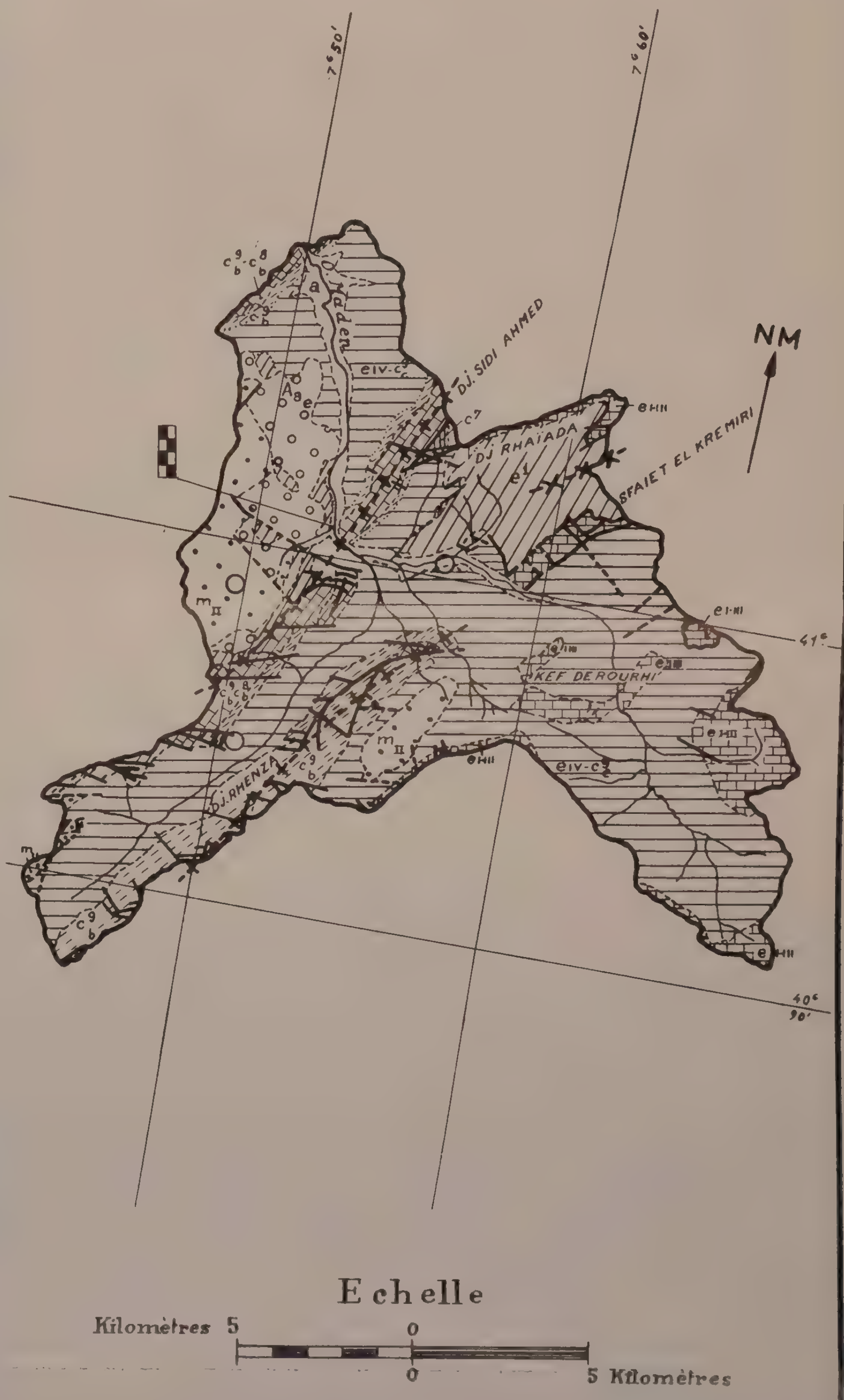
BASSIN VERSANT DE L'OUED ZERGA

Extrait de la carte hydrogéologique de la Calle
au 1/50.000



BASSIN VERSANT DE L'OUED MADEN

Extrait des cartes hydrogéologiques de Nefza
Hédil.Béja.Zaouiet-Madien au 1/50.000



LEGENDE

a	**Alluvions**
A a e	**Eboulis**
m_{II}	**Oligocène** *Alternance de marnes et grès* (Facies Flysch).
e^1	**Priabonien Auversien** *Marnes noires.*
e I-III	**Londinien Lutétien** *Calcaires gris ou noirs bitumeux à patine blanche et silex à la base.*
eIV-c ^9_c	**Paléocène-Maestrichtien supérieur** *Marnes grises à blocaux roux*
c^9_b	**Maestrichtien moyen** *Alternance de marnes et petits bancs calcaires*
c^9_b c^8_b	**Aturien** *Calcaires et marnes.*
c^7	**Campanien inférieur Emschérien** *Marnes noires*

╱	Contacts normaux vus et limites d'affleurements
╱	Contacts normaux supposés sous le recouvrement
╱	Failles et contacts anormaux observés
╱	Failles et contacts anormaux probables
╱	Niveaux repères et bancs durs dans les series marneuses barres gréseuses dans m_{II}
+-+-+-+	Axe anticlinal
×—×—×	Axe synclinal
▚	Station hydrométrique
◎	Pluviographe
○	Pluviomètre
∼	Limite bassin versant

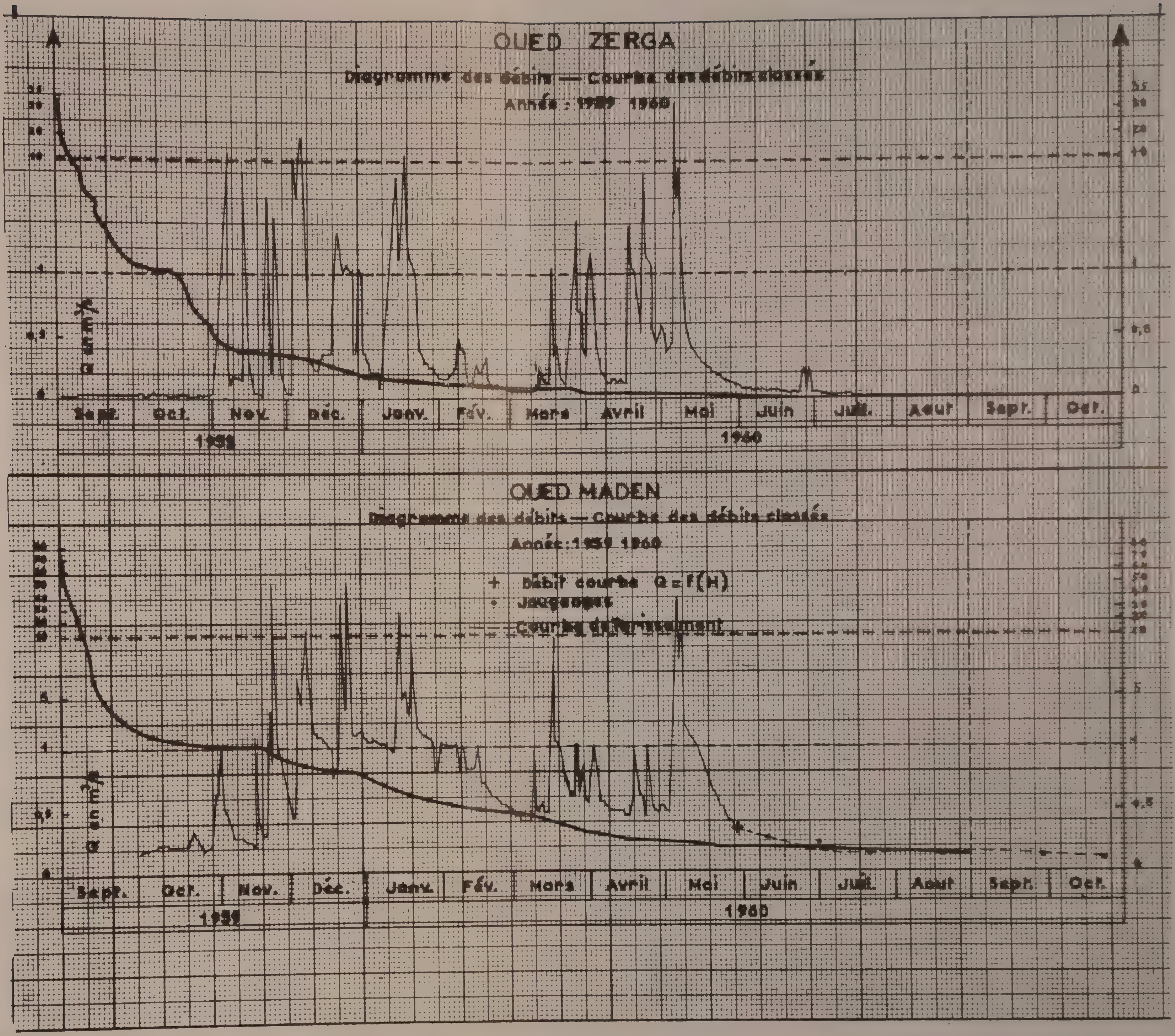

OUED ZERGA
Diagramme des débits — Courbe des débits classés
Année : 1959 1960
35
30
20
10
1
0,5
0
Q en m³/s
Sept.
Oct.
Nov.
Déc.
Janv.
Fév.
Mars
Avril
Mai
Juin
Juil.
Aout
Sept.
Oct.
1959
1960
OUED MADEN
Diagramme des débits — Courbe des débits classés
Année : 1959 1960
+ Débit courbe Q = f(H)
• Jaugeages
Courbe de tarissement
5
1
0,5
0
Q en m³/s
Sept.
Oct.
Nov.
Déc.
Janv.
Fév.
Mars
Avril
Mai
Juin
Juil.
Aout
Sept.
Oct.
1959
1960

Fig. 3

ne sont plus alimentés que par les nappes contenues dans cette formations. L'étude du bilan dynamique des eaux souterraines se ramène à l'étude des courbes de tarissement. Il faut cependant corriger les résultats, des pertes par évaporation et par infiltration dans le lit ces cours d'eau.

Cette méthode ne peut donner qu'une valeur minimum de la productiivté des formations aquifères puisqu'elle néglige toutes les crues de la nappe qui peuvent se produire en saison humide. Afin d'obtenir une valeur plus précise de cette productivité il faudrait séparer dans le diagramme annuel des débits des oueds la partie „écoulement de base" des parties „ecoulement hypodermique" et „ruisellement".

Une connaissance précise de la géologie et de la tectonique de la région étudiée est indispensable pour déterminer notamment le bassin versant hydrogéologique, les formations productrices, les zones de pertes par infiltration etc.

Cette méthode d'estimation a l'avantage de permettre de définir après une année de mesures seulement, les régions où des études hydrogéologiques devront être entreprises, et celles qui sont à éliminer à priori.

Son prix de revient est pratiquement nul puisque les mesures hydrométriques ont en principe pour but la connaissance du bilan des eaux de surface. Elle est d'un grand intérêt pour toutes les études de formations perméables en grand, les procédés hydrogéologiques classiques étant en ce cas trés aléatoires. Il faut cependant remarquer que les caractéristiques hydrodynamiques des formations aquifères devront être obtenues par ces procédés.

Les résultats que nous avons obtenu dans la Tunisie Septentrionale, partie la plus arrosée du pays, illustreront mieux l'intérêt et la limite de cette méthode.

2. 2.*Premier Exemple d'Application. — Bassin dans le flysch oligocène* : (*Oued Zerga*).

2. 2.1. *Situation*

L'oued Zerga est un affiuent rive gauche de l'oued Kébir qui draine les massifs de Kroumirie du Nord Ouest de la Tunisie.

Il prend sa source en Algérie où se trouve une grande partie de son bassin.

2. 2.2. *Caractéristiques du Bassin Versant*

La superficie du bassin versant est de 60 km², l'altitude moyenne du bassin étant de 278 m, tandis que l'altitude de fréquence 1/2 du bassin est 262 m.

La pente moyenne du talweg principal atteint 20,6 m/km pour une longeur de talweg principal égale à 13 km.

Le bassin est boisé sur 89% de sa superficie et couvert de maquis sur 8%, il ne reste donc que 3% de surface non boisée.

2. 2.3. *Caractéristiques Hydrologiques*

La pluviométric durant l'année hydrologique 1959-1960 a atteint 1314 mm, le coefficient d'écoulement est : $c = 0,32$.

Le déficit d'écoulement est : $E = 894$ mm; le module spécifique du bassin a été évalué à 13,3 l/s/km².

2. 2.4. *Caractéristiques Géologiques*

L'oued Zerga draine deux synclinaux oligocènes (faciès Flysch) : le synclinal de Guebour El Aouda et le synclinal de Kef El Mongas séparés par l'anticlinal Priabonien (marnes) d'Aïn Baccouch dont la largeur est réduite. (cf figure 2).

Les plissements de direction Nord-Sud, sont recoupés par des failles transverses très nettes dues à une torsion vers l'Est de la structure. Les plis sont dissymétriques : subverticaux vers l'Est, les grès de l'Oligocène plongent doucement vers l'Ouest en direction de l'Algérie. Du point de vue hydrogéologique le comportement de ces grès doit s'apparenter à la fois à celui de formations poreuses et à celui de formations perméables en grand.

2. 2.5. *Calcul du Bilan*

Le bassin versant hydrogéologique (88 km² environ) de l'oued Zerga est beaucoup plus important que le bassin hydrologique mais le coeur de l'anticlinal d'Aïn Baccouch presqu'uniquement marneux n'est pas susceptible d'emmagasiner des eaux souterraines qui alimenterait l'oued Zerga en période d'étiage. La surface des affleurerements drainés par l'oued Zerga est ainsi réduite à 66 km².

Comme on peut le voir sur la courbe de tarissement, le débit d'étiage est en moyenne de 3,5 l/s. (cf figures 3 et 4).

L'écoulement hypodermique est par contre beaucoup plus élevé, ceci étant dû, principalement, à la forte densité de végétation du bassin.

La largeur moyenne de l'oued est d'environ 2 m sur un parcours de 10 km à l'amont de la station hydrométrique soit une surface de 20.000 m² soumise à l'évaporation. Compte tenu des mesures effectuées sur bac flottant, on peut admettre comme valeur maximum de l'évaporation 10 mm en 10 h.

Le volume évaporé en 10 h serait de 200 m³ soit d'environ 5,5 l/s. Il résulte de ceci que les débits de l'oued jaugés en fin de nuit devraient être nettement supérieurs à ceux mesurés en fin de journée.

Ce fait, exact qualitativement, sera précisé quantitativement au cours de l'étiage 1961, l'oued Zerga se prêtant particulièrement bien à une telle étude par suite de son très faible débit d'étiage.

Les seules possibilités d'infiltrations d'eau à partir de l'oued seraient dans les alluvions, (cf figure 2), qui couvrent 1,9 km². Toutefois par suite de la géologie du bassin, les eaux infiltrées sont redrainées par l'oued en amont de la station de jaugeage.

On peut donc considérer que le débit réel d'étiage est d'environ 9 l/s ce qui équivaut pour les 66 km² d'affleurements gréseux oligocènes à un débit spécifique voisin de 0,15 l/s/km². La hauteur d'eau infiltrée serait donc voisine de 4,5 mm/an. Bien que cette valeur doive être considérée comme minimum puisque établie à partir des seuls débits d'étiage, il ne semble par que la hauteur d'eau réellement infiltrée puisse être beaucoup plus importante.

Ce faible débit spécifique ne peut s'expliquer que par la très faible perméabilité des grès peu fissurés, ce qui est d'autant plus plausible que ces grès sont en alternance avec des marnes. En outre le fort pendage des bancs gréseux et la forte dénivelée de la topographie favorisent l'écoulement rapide des eaux et limitent d'autant les possibilités d'infiltrations dans les grès.

On peut donc en conclure qu'il n'existe pas de nappe souterraine puissante dans tout le bassin versant géologique de l'oued Zerga. Compte tenu des résultats des autres stations hydrométriques de la région, les recherches d'eaux souterraines dans l'Oligocène de la Tunisie Septentrionale risquent d'être fort décevantes. On est par conséquent amené à orienter les études vers la récupération des eaux de surface.

Le déficit d'écoulement de 894 mm, pour l'année 1959-1960 semble être dû à l'évapotranspiration, la région étant particulièrement boisée. De nouvelles études sont en cours pour vérifier cette hypothèse.

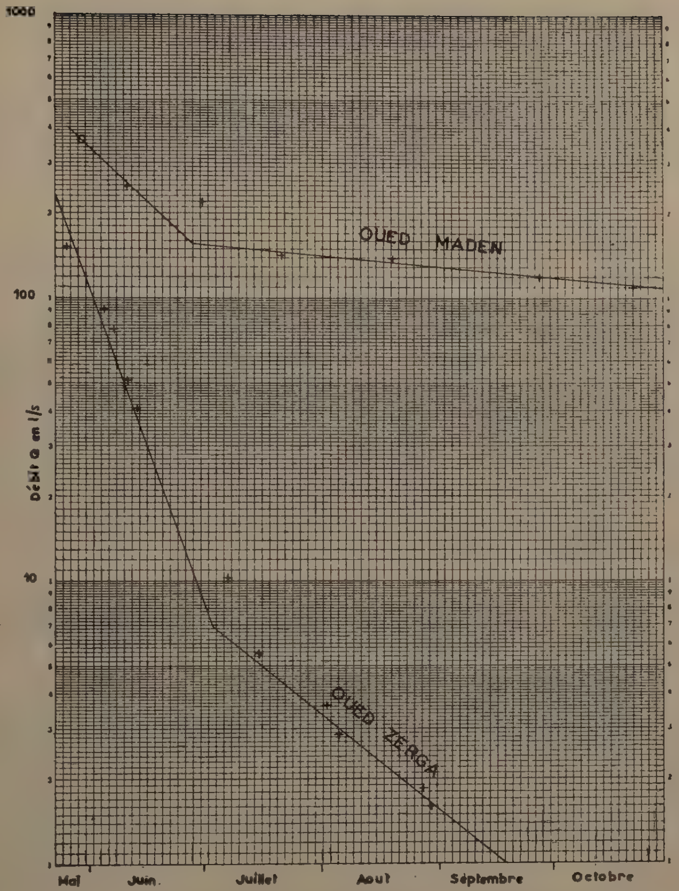


Fig. 4

2. 3. *Deuxième Exemple d'Application — Bassin dans les calcaires campanien et éocene* : (*Oued Maden*).

2. 3.1. *Situation*

L'oued Maden se situe à la limite de la Kroumirie et de la région des Mogods. Il est affluent rive droite de l'oued Malah

Son bassin se trouve en grande partie dans les. Mogods calcaires.

2. 3.2. *Caractéristiques du Bassin Versant*

La superficie du bassin versant est de 157 km², l'altitude moyenne du bassin est de 321 m tandis que l'altitude de fréquence 1/2 est de 320 m.

La pente moyenne et la longueur des deux talwegs principaux sont respectivement de :

(1) 19 m/km pour 16 km
(2) 20 m/km pour 20 km

La région est très peu boisée sur 6 % de sa surface, avec un maquis clairsemé sur 10% le reste soit 84% ne porte pas de couverture végétale.

2. 3.3. *Caractéristiques Hydrologiques*

La pluviométrie pendant l'année 1959—1960 a été de 840 mm; le coefficient d'écoulement étant c = 0,37 il en résulte que le déficit d'écoulement est : E = 530 mm.

3. 3.4. *Caractéristiques Géologiques*

Les plis serrés sont parallèles entre eux et alignés SW–NE. Les anticlinaux coffrés et étroits alternent avec de larges synclinaux à fond plat. (cf figure 2).

L'oued Maden draine les deux anticlinaux aturiens du djebel Rhenza et de Sidi Ahmed, et quelques lambeaux éocónes formant buttes témoins dont les principaux sont : Le Kef Derourhj et Sfaïet El Kremiri ainsi que le synclinal de djebel Rhaïada fortement redressé vers le NE.

La dalle calcaire éocène puissante d'une centaine de mètres est interstratifiée entre deux masses marneuses — 800 m de Dano-Montien à la base, et 1000 m de Lutétien supérieur — Priabonien au sommet.

2. 3.5. *Calcul du Bilan*

La bassin versant hydrologique est ici presque confondu avec le bassin hydrologique. Toutefois par suite de la présence des épaisses séries marneuses, que nous avons signalé, la surface des affleurements productifs se réduit à environ :

22 km² pour les calcaires de l'Éocène
33 km² pour les calcaires du Campanien.

La courbe de tarissement montre que le débit d'étiage est voisin de 130 l/s. (cf figures 3 et 4).

La largeur moyenne de l'oued est estimée à 3 m pour un parcours moyen de 35 km à l'amont de la station de jaugeage, soit une surface voisine de 100.000 m² soumise à l'évaporation. Comme précédemment on peut admettre comme valeur maximum de l'évaporation 10 mm en 10 h. Le volume évaporé en 10 h serait de 1.000 m³ soit environ 25 l/s.

Les possibilités d'infiltration sont pratiquement nulles, le substratum sur lequel coule l'oued étant marneux.

On peut donc considérer que le débit réel d'étiage de l'oued Maden est d'environ 155 l/s pour 55 km² d'affleurements calcaires soit de 3,0 l/s/km², ce qui correspond à une hauteur d'eau infiltrée de 90 mm/an.

Ces valeurs ne représentent que des minima (cf paragraphe 2.1.), puisque calculées à partir des seuls débits d'étiage; elles ne s'appuyent en outre que sur les données d'une seule année de mesures.

Un bilan plus précis nécessiterait des observations portant sur plusieurs années et l'installation de piézomètres dans les massifs calcaires pour suivre les variations de niveau du plan d'eau (cf communication de MM. J. Tixeront, E. Berkaloff, A. Caine, E. Mauduech n° 5 de la Bibliographie).

Le débit spécifique est nettement plus grand que celui des grès de Kroumirie; cela peut être dû au moins en partie aux nombreuses failles affectant les calcaires. Les fractures y sont plus franches et ont pu être élargies par dissolution du calcaire.

Le volume important des réserves en eaux souterraines dans les calcaires est en partie la cause d'un coefficient d'écoulement plus élevé que ceux des bassins argilo-gréseux de Kroumirie, malgré une pluviométrie plus faible.

Le déficit d'écoulement est de 530 mm au lieu de 800 à 900 mm en Kroumirie, ce qui s'explique par le fait qu'une partie des eaux de pluie percole dans les calcaires et se trouve ainsi soustraite à l'évaporation, et par le fait que la faible végétation limite les pertes par évapotranspiration.

Des jaugeages différentiels sont en cours pour déterminer l'apport dû à chaque affleurement. Il est, en effet, possible que les calcaires du Campanien, plus tectonisés que ceux de l'Éocène, puissent avoir un débit spécifique plus important.

3. NAPPES DE FORMATIONS DUNAIRES — ESTIMATION DES RESSOURCES DYNAMIQUES PAR JAUGEAGES DIFFÉRENTIELS.

Pour déterminer l'apport en eau d'un affleurement drainé par un oued, il existe des cas où des mesures de débit, l'une en amont des résurgences provenant de l'affleurement, l'autre en aval, permettent d'en évaluer le débit spécifique.

Ces mesures doivent être effectuées en période d'étiage afin d'éviter que le ruissellement entre les deux stations ne vienne perturber les mesures.

Dans le cas des dunes, où la nappe d'eau est généralement phréatique, le bilan des ressources dynamiques est pratiquement inabordable par les procédés classiques d'essais de pompage. Pour bien conduire ces essais il faudrait disposer d'un grand nombre de piézomètres très rapprochés d'un sondage souvent difficile à développer.

3. 1. *Exemple d'Application — Bassin dans les dunes de Nefza.*

3. 1.1. *Situation*

La partie Est des dunes de Nefza forme une entité hydrogéologique drainée par les oueds Ahmar Nord et Sud qui se jettent dans l'oued Malah.

3. 1.2. *Caractéristiques du Bassin Versant*

La superficie de cette partie des dunes est de 20 km^2 environ. L'altitude moyenne est de 56 m. Ces dunes ne sont pratiquement pas boisées.

3. 1.3. *Caractéristiques Hydrologiques*

La pluviométrie moyenne de la région (poste de Tabarka) calculée sur le période de 1901 à 1950 est de 1.029 mm.

3. 1.4. *Caractéristiques Géologiques*

Un dôme dû, soit au prolongement vers le NE de l'anticlinal du Djebel Srhir soit à un diapir triasique, empêche l'écoulement des eaux souterraines vers l'Ouest c'est-à-dire vers la mer. Vers le sud les dunes se terminent au contact des marnes du Lutétien Supérieur-Priabonien du synclinal de Djebel Kreroufa. Ces dunes reposent sur un substratum formé par les marnes du Dano-Montien.

3. 1.5. *Calcul du Bilan*

Des mesures de débit d'étiage, à deux stations de l'oued Malah, l'une avant le confluent avec l'oued Ahmar Sud drainant les dunes, l'autre après la traversée des dunes à proximité du Djebel Bou Lahia, donnent une différence de débit de l'ordre de 300 l/s.

La largeur moyenne de l'oued Malah entre les deux stations distantes de 10 km environ, varie entre 5 et 10 m; le volume évaporé par la surface de l'oued sur cette distance est compris entre 500 et 1.000 m³ en 10 heures soit un débit de l'ordre de 20 l/s.

On peut considérer que l'apport des dunes représente à peu près 320 l/s pour une surface de 20 km² soit 16 l/s/km². La hauteur d'eau infiltrée est donc voisine de 480 mm.

Le débit spécifique est ici très important, ce qui s'explique par la très grande perméabilité* des sables dunaires, ainsi que par l'absence de végétation sur ces dunes. Néanmoins ces sables favorisent la remontée des eaux par capillarité donc les pertes par evaporation.

Des études sont actuellement en cours pour déterminer le mode de captage le plus approprié des énormes ressources en eaux souterraines de ces dunes.

BIBLIOGRAPHIE

(1) Carte Géologique Provisoire de la Tunisie au 1/200.000. Feuilles : Sousse — Maktar — Tunis.

(2) Carte Géologique de la Tunisie au 1/50.000. Feuille : Zaouiet Madien.

(3) Minute de la Carte Hydrogéologique de la Tunisie au 1/50.000. Feuilles : Nefza — Hédil — La Calle — Djebibina — Sidi Bou Ali.

(4) J. Tixeront et E. Berkaloff — „Note sur la percolation profonde des précipitations d'eau dans les massifs calcaires en Tunisie" C.R. Association Internationale d'Hydrologie Scientifique — Assemblée Générale d'Oslo 1948. Tome III-pp 31–39.

(5) J. Tixeront — E. Berkaloff — A. Caine — E. Mauduech — „Bilan d'eau des massifs calcaires en Tunisie" C.R. Association Internationale d'Hydrologie Scientifique — Assemblée de Bruxelles 1951 — Tome IV - pp 47–53.

(6) Rapport Sogréah R 7036 — „Aménagement de l'Oued Nebaana — Périmètre Irrigable du Bled Sisseb — Étude Hydrogéologique" par F. Bazin et A. Bonnier.

(7) Rapport S.C.E.T. — I.R.H. 036 — „Tunisie Septentrionale — Annuaire Hydrométrique" par J. Prost.

(*) Même pendant les plus fortes pluies on n'observe pas de ruissellement sur les dunes.

LABORATORY TESTS ON TEST DRILLING SAMPLES FROM RECHNA DOAB, WEST PAKISTAN. AND THEIR APPLICATION TO WATER RESOURCES. EVALUATION STUDIES

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ABSTRACT

Water resources investigations have been undertaken in Rechna Doab between Rivers Ravi and Chenab, in West Pakistan, in connection with water-logging and salinity control projects. Studies made include a detailed geological, earth resistivity and soil survey, test drilling, aquifer performance tests, well inventory, stream gauging and water quality investigations. Test hole samples down to dephts of 600 ft. were tested in the laboratory for properties such as grain size distribution, porosity, permeability and moisture equivalent.

In the Rechna Doab, laboratory studies and the geological and hydrological studies correlate favourably. Interpretation of the laboratory data has helped in zoning the sub-surface alluvium into the coarser and more permeable stream bed and meander belt deposits and the finer and less permeable flood plain deposits. This has resulted in the location of, what appear to be, buried ground-water channels.

Using the laboratory data, coefficients of permeability, transmissibility and storage have been computed for the aquifer at each test hole. Based on these hydraulic properties, the aquifer in Rechna Doab has been zoned and these zones have been mapped.

In as much as none of the present quantitative techniques of hydrological investigations is perfect in itself, it has been suggested that the results of the laboratory tests on sub-surface samples may be used for making a quantitative evaluation of the water resources of an area. This technique may be extended to supplement other quantitative methods in order to make a more accurate evaluation of the water resources of a region.

1. INTRODUCTION

Rechna Doab is a part of the vast alluvial plain of the Indus and its tributaries and is located in the northeastern part of West Pakistan, between Rivers Ravi and Chenab (Fig. 1a). It covers an area of 11,000 square miles. In recent years, the intensive application of irrigation water together with inadequate sub-surface drainage, has resulted in extensive waterlogging and salinization of land in the Rechna doab as well as in the whole of the Indus plain. In order to devise anti-salinity and anti-waterlogging measures, an extensive program of hydro-geological investigations was launched in 1955. Investigations included a geological, geophysical and soil survey of the area, extensive test drilling, aquifer performance tests, collection of groundwater level data, analysis of well hydrographs, stream gauging and water quality investigations. Test hole samples, upto dephts of 600 ft. were tested in the laboratory of the Land Reclamation Department, for properties such as grain size distribution, porosity, permeability and centrifuge moisture equivalent.

The laboratory work was originally started so as to provide a check on the hydrological field data. As the studies continued, the laboratory data was compiled, studied and analysed by the author and it became increasingly evident that the geological and hydrological properties of the sub-surface strata, as deduced from the laboratory data, correlate favourably with the geological and hydrological field studies. The results of this study have been discussed in detail in the following pages.

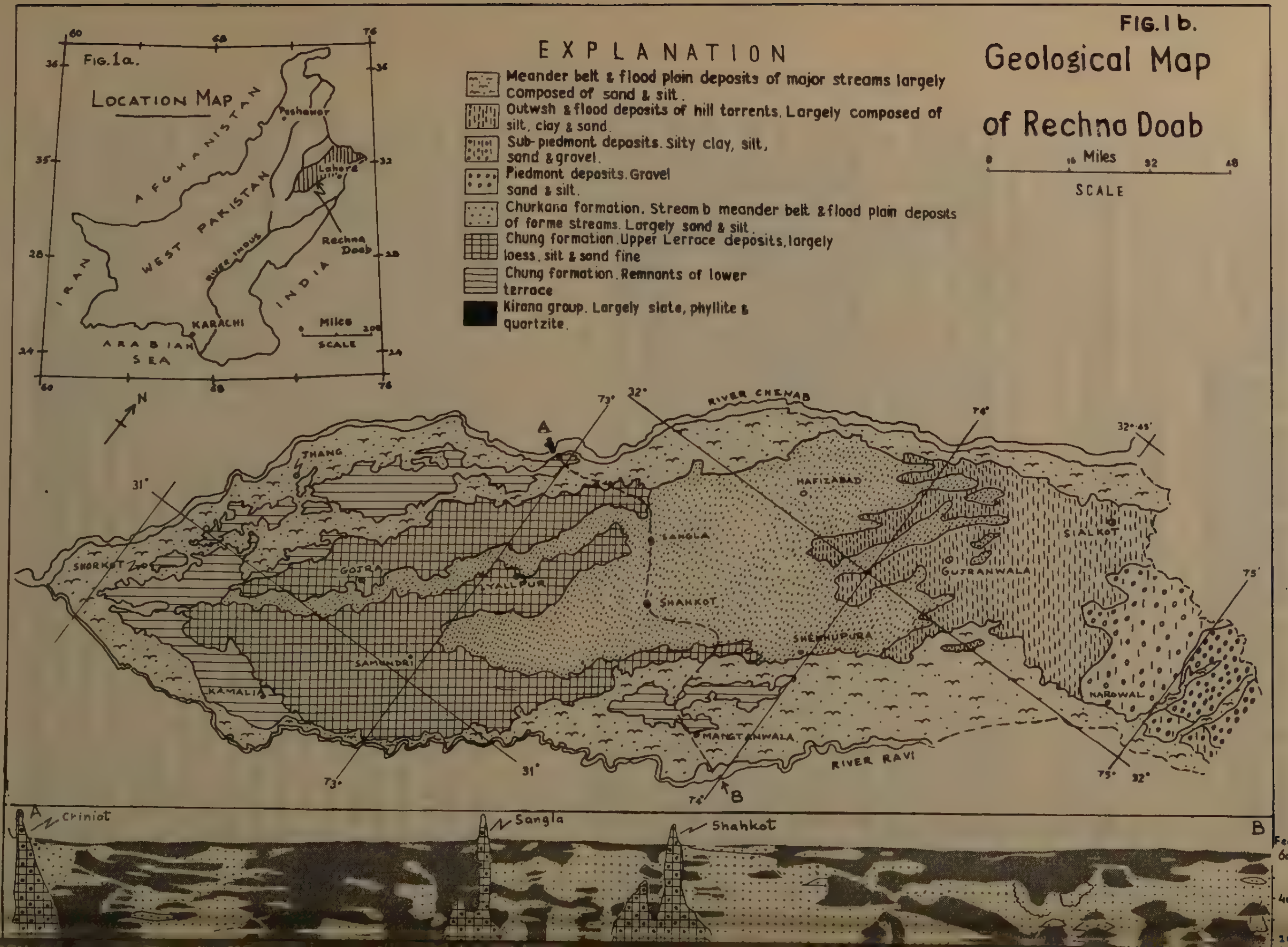


FIG. 1 b.

Geological Map of Rechna Doab

Fig. 1a. LOCATION MAP

EXPLANATION
Meander belt & flood plain deposits of major streams largely composed of sand & silt.
Outwsh & flood deposits of hill torrents. Largely composed of silt, clay & sand.
Sub-piedmont deposits. Silty clay, silt, sand & gravel.
Piedmont deposits. Gravel sand & silt.
Churkana formation. Stream b meander belt & flood plain deposits of forme streams. Largely sand & silt.
Chung formation. Upper Lerrace deposits, largely loess, silt & sand fine
Chung formation. Remnants of lower terrace
Kirana group. Largely slate, phyllite & quartzite.
0
16 Miles
32
48
SCALE
60
68
76
36
35
28
24
AFGHANISTAN
IRAN
WEST PAKISTAN
INDIA
Peshawar
Lahore
Rechna Doab
RIVER INDUS
KARACHI
ARABIAN SEA
0 Miles 200
SCALE
N
A
B
73°
74°
75°
31°
32°
32°-45'
RIVER CHENAB
RIVER RAVI
JHANG
SHORKOT
GOJRA
LYALLPUR
SAMUNDRI
KAMALIA
SANGLA
SHAHKOT
HAFIZABAD
SHEKHUPURA
MANGTANWALA
GUJRANWALA
SIALKOT
NAROWAL
Criniot
Sangla
Shahkot
Feet
600
400
200

2. GEOLOGY

Rechna doab is a complex alluvial plain. It consists of piedmont and sub-piedmont plains, covered by piedmont deposits, in the northeastern corner of the doab. Southwestward it is followed by a central, slightly raised and relatively flat table-land, bounded by the flood plains of the Ravi and the Chenab. The central upland or the interfluve consists of three distinct geomorphic and geologic zones. These are : — (1) The Daska plain, which is an uplifted flood plain covered by outwash deposits; (2) the ancient flood plain and meander belts of the Chenab, containing its former flood plain deposits referred to as the Chuharkana formation (Kazmi 1955); and (3) the "Bar" upland, which is largely covered with the loess deposits of the Chung formation (Kazmi 1955). All these physical features and the related geological deposits are of Quaternary age. The only rock outcrops seen in the area consist of Pre-Cambrian slates, phyllites, and quartzites of the Kirana group (Heron 1913; Kazmi 1955), that occur as monadnocks, near Shahkot, Sangla and Chiniot (Fig. 1b and c).

Gravity survey and the test drilling data indicate that the maximum thickness of the Quaternary deposits may be upto 2000 ft. However in the central part of the doab, between Shahkot and Chiniot, the thickness of these deposits is only 300-600 ft (Fig. 1 c).

On the surface, the alluvial deposits show a recurring pattern of typical flood plain deposits, e.g. point bars and swales, clay plugs in the cut-off meanders and oxbows, levees and backswamp deposits. These deposits may be classified into two hydrogeological units; the finer, thinner, relatively more uniform but less permeable flood plain deposits and the coarser, thicker, and more permeable stream bed and meander belt deposits. Though these two units could be easily mapped on the surface, it was not possible to delineate these zones in the subsurface on the basis of the test hole data alone (Fig. 1 c). But the geology of the area indicates that in the geological past, as the rivers oscillated back and forth, deposits of these two groups have overlapped, and have been stacked one above the other. Thus it would be logical to expect in the subsurface alluvium certain zones, in which the thickness of the finer flood plain deposits would be greater and others in which the thickness of the coarser meander belt deposits would be greater. If this were true, it should be reflected in the physical properties of the sediments from the test holes. And the laboratory studies do confirm these deductions as has been shown in the following pages.

3. LABORATORY TESTS

3. 1. *Drilling and Sampling*

Failings and Franks 1500 rotary rigs were used for test drilling. Sand, silt and clay samples from test holes were collected from the circulating mud, by hand or with the help of sieves, were gently rinsed with water to remove the mud, were megascopically examined in the field for making the lithologic log, and were packed in sample bags and despatched to the laboratory.

3. 2. *Laboratory Tests*

In order to achieve uniformity in the results, standardised techniques were used in the laboratory, and where necessary tests were duplicated on quartered samples. Preparation of samples for tests included prodecures such as crushing, disaggregation, washing, sieving and splitting. Mechanical analyses (sieve and hydrometer) were performed on all samples. Samples were tested for specific gravity, (pycnometer method) porosity (paraffin method), moisture equivalent (centrifuge method) and permeability (using constant head type permeameter).

3. 3. *Mechanical analysis*

Grainsize cumulative frequency curves have been plotted from the mechanical analysis of each sample. Each curve has been statistically analysed and properties of sediments such as sorting, symmetry, peakedness and the proximate admixture ratios have been calculated and used for describing and comparing the samples (Fig. 2.). For an average thickness of 600 ft. of sediments penetrated by each test hole, the average values of median grain size (Md) and the log of the coefficient of assortment (log. So) has been obtained by taking the mean of all the samples tested from that hole. These have been plotted on a map and based on these values, the subsurface sediments have been zoned as shown in Figs. 3 and 4.

3. 4. *Specific gravity, porosity and moisture equivalent.*

These tests have been used to calculate the specific yield of the samples, using the formulae : —

$$\begin{array}{c} \text{Specific} \\ \text{retention} \end{array} = \begin{array}{c} \text{Centrifuge} \\ \text{moisture} \\ \text{equivalent} \end{array} \times \begin{array}{c} \text{Correction} \\ \text{factor} \\ \text{(from tables)} \end{array} \times \begin{array}{c} \text{Apparent} \\ \text{Sp. gr.} \end{array}$$

$$\text{and Sp. yield} = \text{Porosity} - \text{Sp. retention.}$$

Specific yields of 76 samples from 7 test holes, thus calculated, have been shown in Fig. 5. From this data the average specific yields of various grades of sediments have been computed and have been used to calculate the mean specific yield for a thickness of 400 ft of sediments penetrated by each test hole. Based on this average specific yield, the subsurface sediments in the Rechna doab have been zoned as shown in Fig. 6.

PERMEABILITY

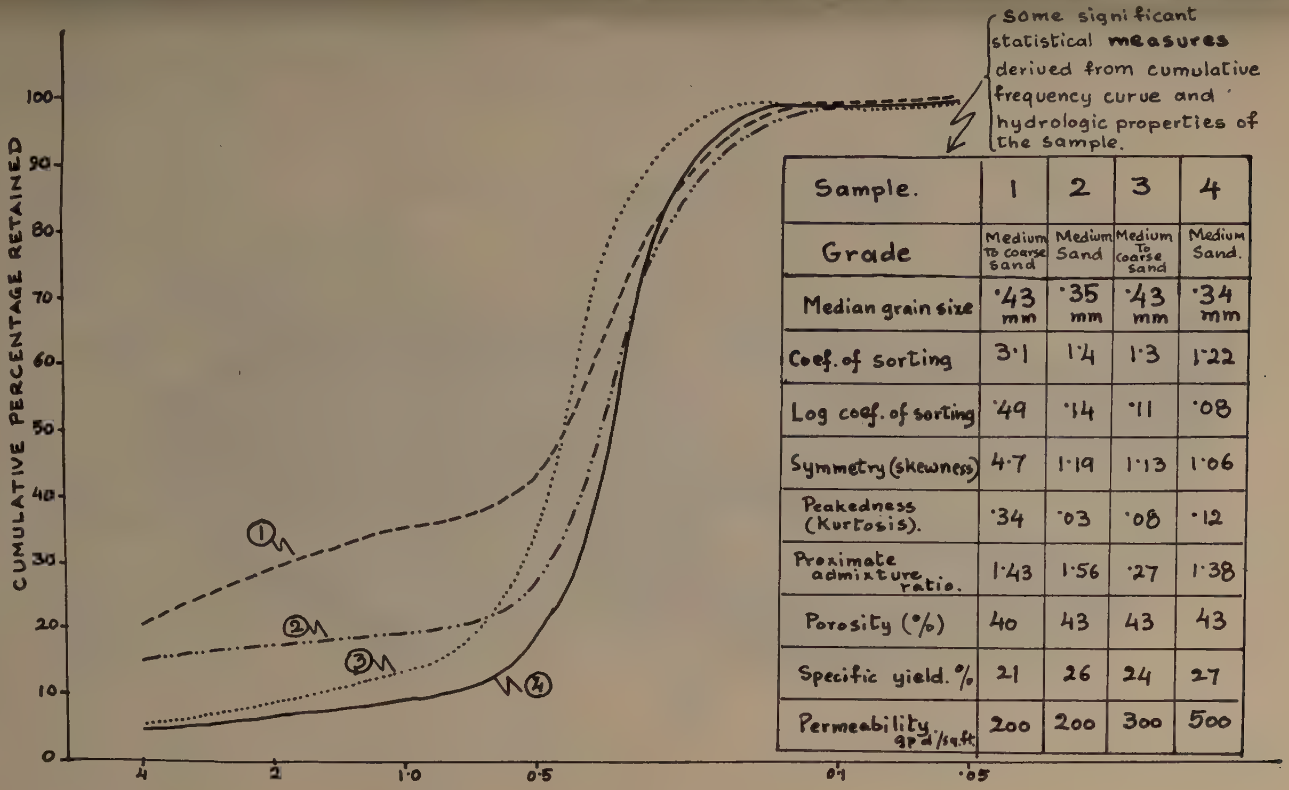
For a thichness of 400 ft of sediments at each test hole, the average coefficient of permeability has been computed by taking the mean of all the samples tested from that test hole. Based on this property the aquifer in the Rechna doab has been zoned as shown in Fig. 7.

Coefficient of transmissibility (for a depht of 400 ft only from the surface), has been computed by multiplying the average permeability of sediments at each test hole by the total thickness of the aquifer at that point and a transmissibility map, based on this data has been compiled as shown in Fig. 8.

4. CORRELATION OF LABORATORY STUDIES WITH HYDROGEOLOGICAL FIELD STUDIES

4. 1. *Properties of the Aquifer*

Lithologic logs of 250 test holes and the laboratory tests on thousands of samples from these holes in Rechna doab indicate that the groundwater aquifer in this area is largely composed of fine to medium sand, medium sand, or medium to coarse sand (Fig. 2), with relatively thin layers, lenses or intercalations of very fine sand, silty sand or silt and clay. The sands exhibit a fair to good degree of assortment (average So = 1.5 to 2), the average porosity is about 40%, the average specific yield about 25% and the average permeability varies from about 100-500 gallons per day per sq. ft. The finer sediments, however, show a greater degree of variation in their properties, particularly the silty fine sands, and layers with admixtures of gravel,



Some significant statistical **measures** derived from cumulative frequency curve and hydrologic properties of the sample.

Sample.	1	2	3	4
Grade	Medium To coarse sand	Medium Sand	Medium To coarse sand	Medium Sand.
Median grain size	·43 mm	·35 mm	·43 mm	·34 mm
Coef. of sorting	3·1	1·4	1·3	1·22
Log coef. of sorting	·49	·14	·11	·08
Symmetry (skewness)	4·7	1·19	1·13	1·06
Peakedness (Kurtosis).	·34	·03	·08	·12
Proximate admixture ratio.	1·43	1·56	·27	1·38
Porosity (%)	40	43	43	43
Specific yield. %	21	26	24	27
Permeability gpd/sq.ft.	200	200	300	500

Fig. 2 — Grain size in millimeters

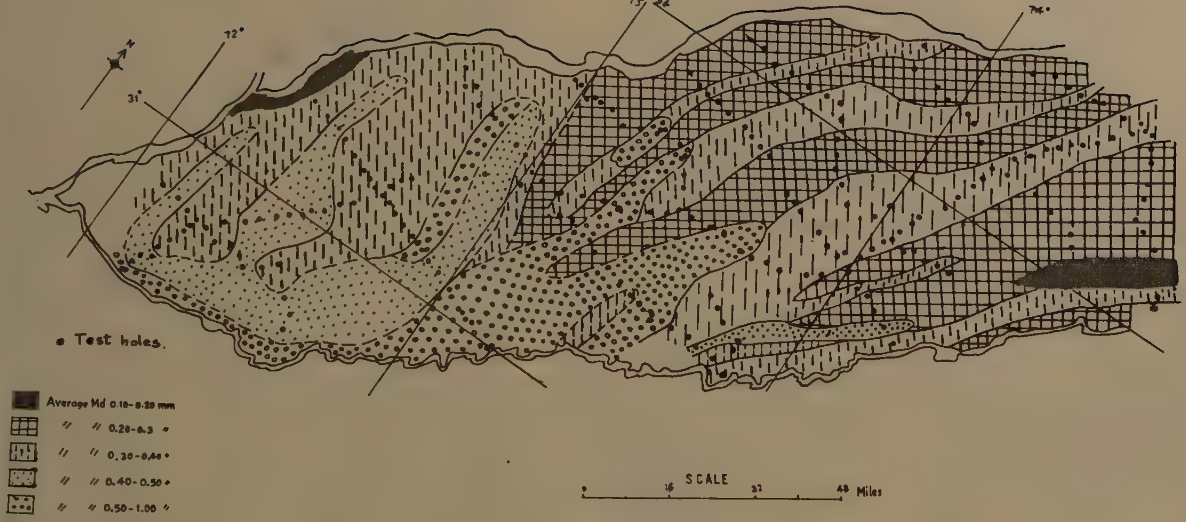

72°
31°
73°
32°
74°
N
• Test holes.
Average Md 0.10-0.20 mm
// // 0.20-0.3 //
// // 0.30-0.40 //
// // 0.40-0.50 //
// // 0.50-1.00 //
SCALE
0
16
32
48 Miles

Fig. 3

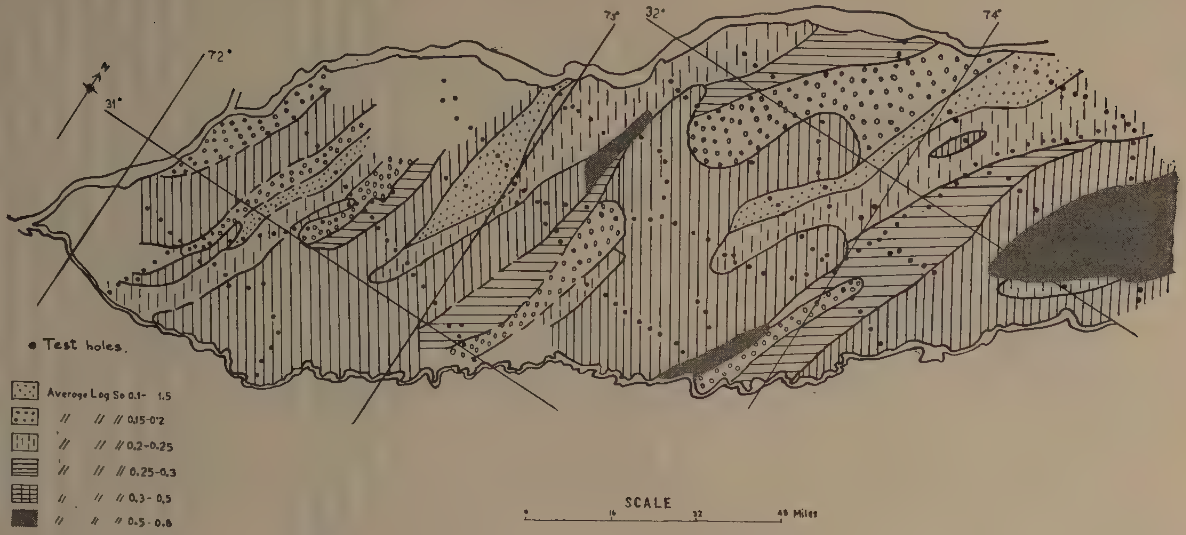

N
72°
31°
73°
32°
74°
• Test holes.
Average Log So 0.1- 1.5
" " " 0.15-0.2
" " " 0.2-0.25
" " " 0.25-0.3
" " " 0.3- 0.5
" " " 0.5- 0.8
SCALE
0
16
32
48 Miles

Fig. 4

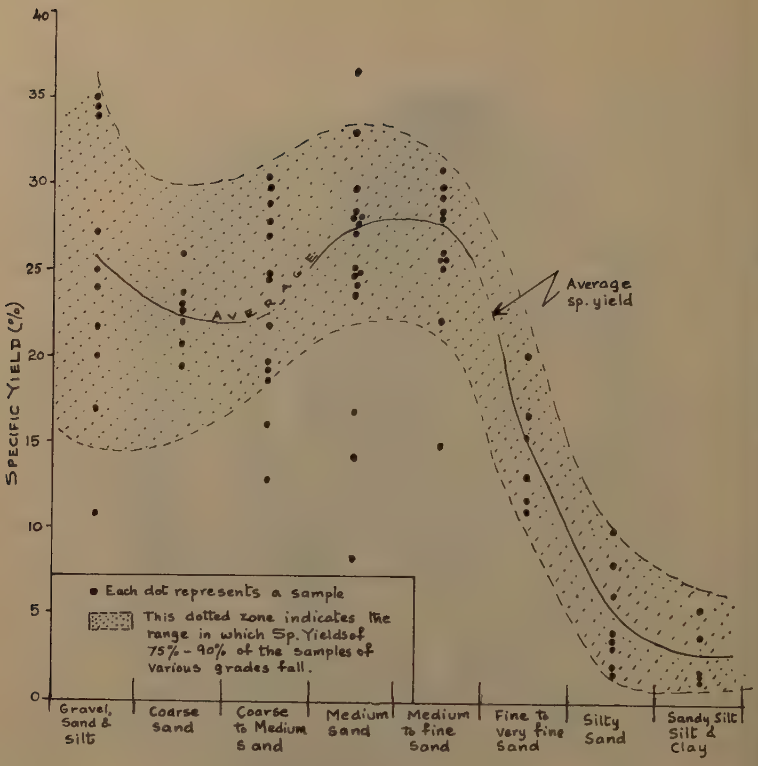


Fig. 5

sand, silt and clay.Lab tests indicate that these may be effective aquicludes and have extremely low permeabilities and specific yields in one area, or at one horizon, yet at others, they may be in the form of poor aquifers, with appreciable permeabilities (upto 50 gpd/sq. ft.) and specific yields (upto 10%). Thus from a lithologic log alone it is not possible to differentiate such poor aquifers from the aquicludes.

4. 2. *Correlation of Laboratory and Field Data.*

Under the water table conditions the specific yield of an aquifer equals coefficient of storage. Thus the coefficient of storage as deduced from the behaviour of the rising water table (Fig 9), in Rechna Doab varies from 0.2 to 0.3 (Tipton and Kalmbach — 1959). As deduced from the laboratory studies, the average storage coefficient for the entire aquifer in the Rechna Doab, is 0.17; in the northeastern part of the doab the aquifer has an average specific yield of about 0.14; in the central zone (largely waterlogged) the average is about 0.2 and in the southeastern portion of the doab the average is 0.19. However these figures are much higher than those obtained from aquifer tests according to which the storage coefficient ranges from 0.0016 to 0.073 at various locations (Wapda 1959). This wide range of variation is readily explained by the fact that some of the sand zones between the clay layers, in the pumped wells, have probably been under artesian or semi-artesian pressure.

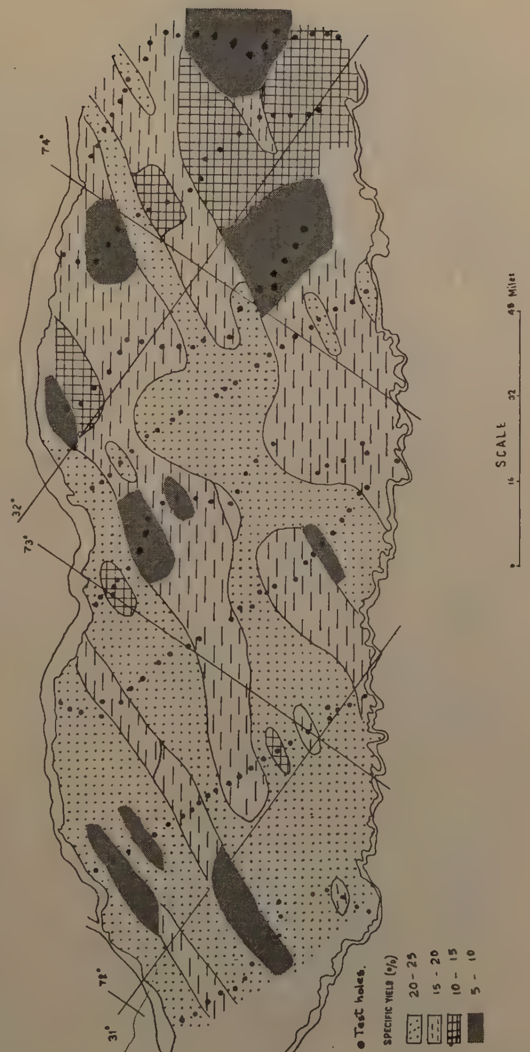
74°
32°
73°
72°
31°
● Test holes.
SPECIFIC YIELD (%)
20 - 25
15 - 20
10 - 15
5 - 10
SCALE
0
16
32
48 Miles

Fig. 6

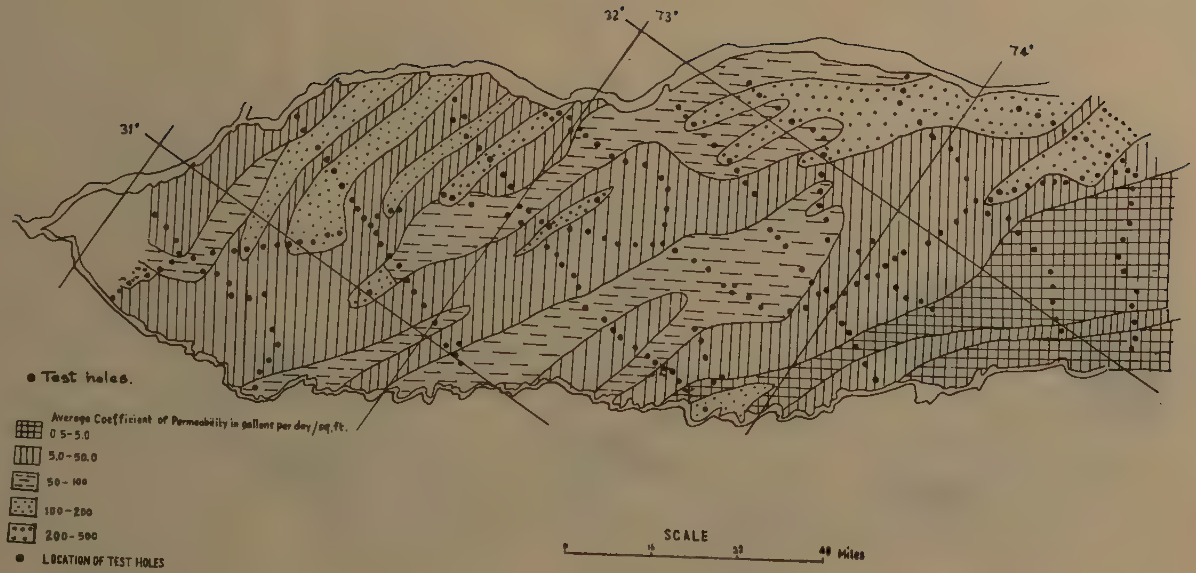

31°
32°
73°
74°
● Test holes.
Average Coefficient of Permeability in gallons per day/sq.ft.
▦ 0 5-5.0
▥ 5.0-50.0
▤ 50-100
▨ 100-200
▨ 200-500
● LOCATION OF TEST HOLES
SCALE
0
16
32
40 Miles

Fig. 7

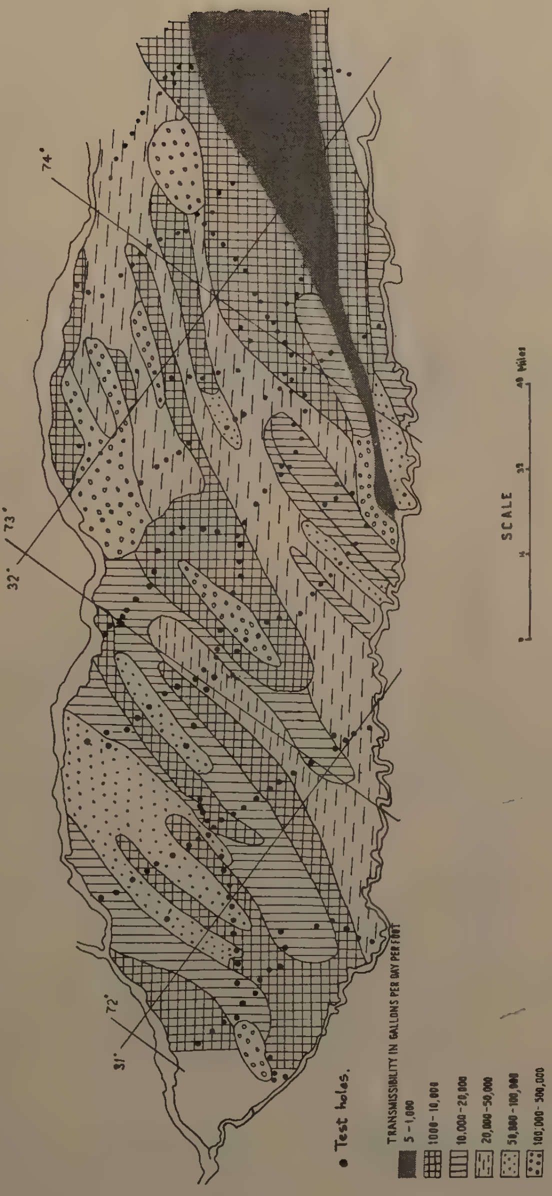

74°
73°
32°
72°
31°
● Test holes.
TRANSMISSIBILITY IN GALLONS PER DAY PER FOOT
▩ 5 - 1,000
▦ 1000 - 10,000
▥ 10,000 - 20,000
▤ 20,000 - 50,000
▨ 50,000 - 100,000
▨ 100,000 - 300,000
SCALE
0
40 Miles

Fig. 8

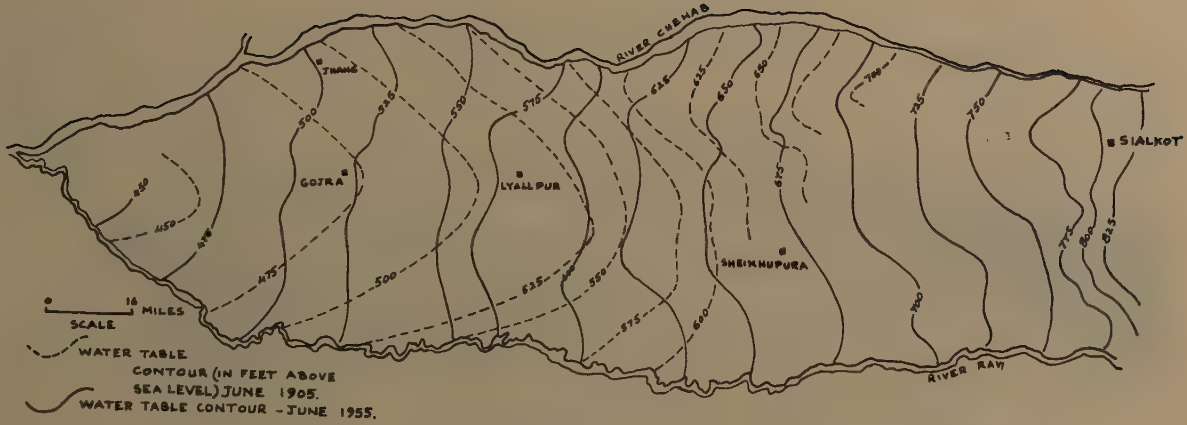

RIVER CHENAB
RIVER RAVI
SIALKOT
SHEIKHUPURA
LYALLPUR
GOJRA
JHANG
825
800
775
750
725
700
675
650
625
600
575
550
525
500
475
450
SCALE
0
16 MILES
WATER TABLE CONTOUR (IN FEET ABOVE SEA LEVEL) JUNE 1905.
WATER TABLE CONTOUR - JUNE 1955.

Fig. 9

The coefficients of transmissibility as computed from laboratory data for various test wells are consistently lower than the figures obtained through aquifer tests on these wells (Fig. 10). Part of this discrepancy in the two results may be due to the following facts:

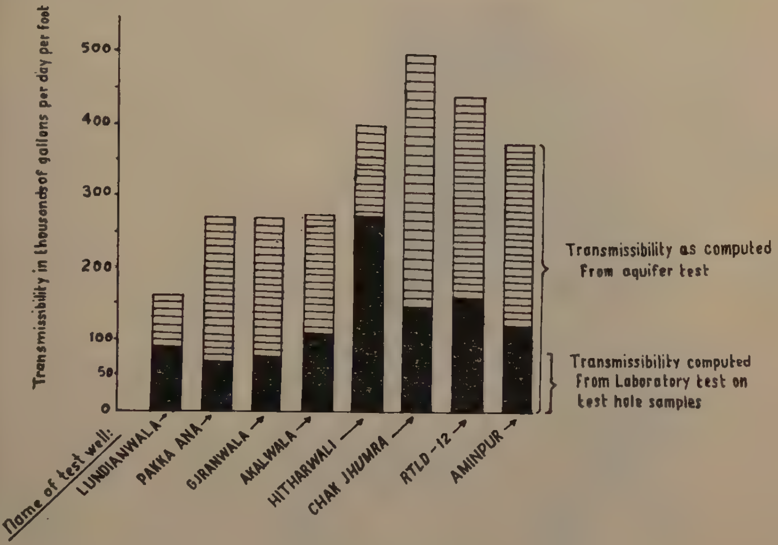


Fig. 10

1) No temperature corrections are made while computing the field permeabilities and transmissibilities;

2) The test wells did not penetrate the entire aquifer, as generally assumed while applying the non-equilibrium furmulae;

3) In the lab, the samples were packed in the permeameter tube by ramming them down with a mallet, which probably resulted in much greater compaction of the sediments for the permeability test, than actually occurs in nature;

4) While reporting the lab permeabilities, mean of several readings were taken, rather than the highest value (the peak of the permeability — time curve), which is now the standard practice.

All these errors have been cumulative in one direction and have resulted in this vast difference in the transmissibilities as calculated from lab tests and as deduced from pumping tests. However, consistency in errors, (due to consistency in the methods) have resulted in a more or less uniform variation, and the lab permeabilities or transmissibilities may be multiplied by a correction factor of approximately 3 to convert these into the field coefficients of permeability or transmissibility.

The thickness of the aquifer (i. e. the sand layers) down to a depth of 400 ft. is maximum (300-400 ft) in the central part of the doab (Fig. 11.) It is generally less than 200 ft in the northeastern corner of the doab, and along the margins in the recent flood plain zones.

Maps depicting the physical and hydrological properties of the aquifers, as shown in figures 3,4,6,7,8,11 and 12 clearly bring out the following points:

1) The properties of the aquifer vary considerably within short distances. Along each line of test holes, there are alternate zones of relatively high and low average median grain size (Fig. 3); better and poorer asssortment of sediments (Fig. 4);

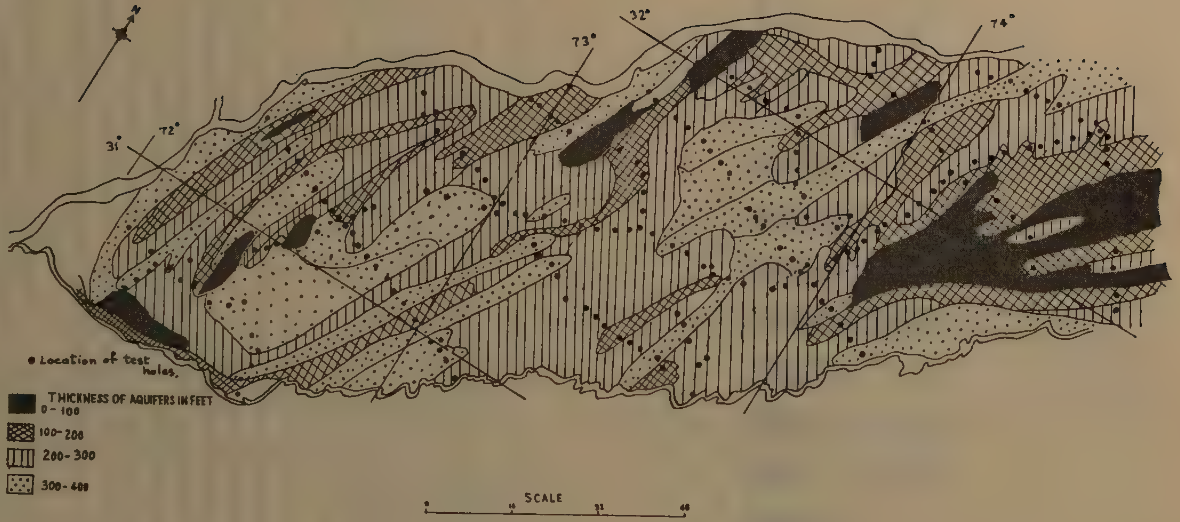
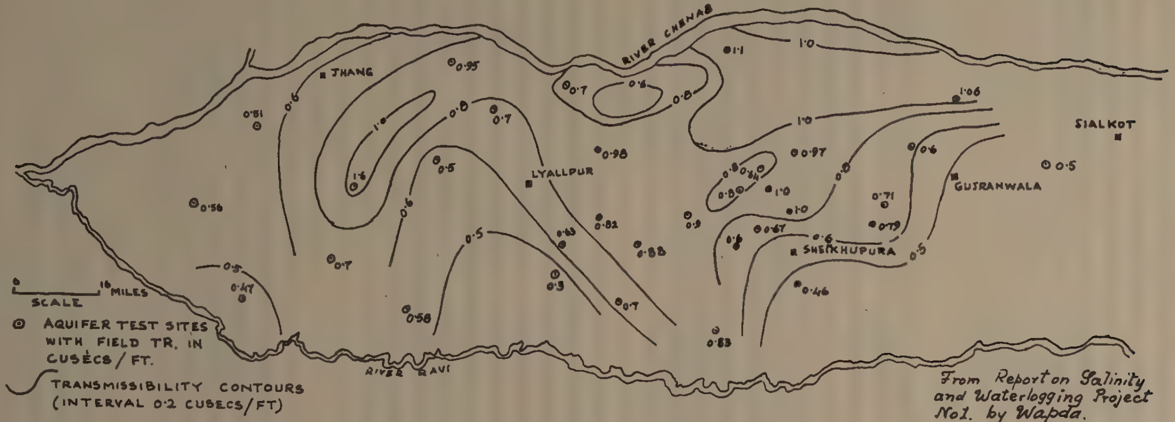

N
31°
72°
73°
32°
74°
● Location of test holes.
THICKNESS OF AQUIFERS IN FEET
0 - 100
100-200
200-300
300-400
SCALE
0
16
32
48

Fig. 11



From Report on Salinity and Waterlogging Project No1. by Wapda.

Fig. 12

thicker and thinner aquifer (Fig. 11), higher and lower permeability (Fig. 7), transmissibility (Fig. 8 and 12), and specific yield (Fig. 6).

2) When these zones are connected, they produce a linear pattern, with a general northeast-southwest trend. This pattern conforms to the general trend of the abandoned river channels shown in Fig. 1b. It is therefore reasonable to conclude that the zones of maximum thickness of aquifers in figure 11, and of maximum permeabilities, transmissibilities and specific yields in figures 7,8, and 6, correspond to those sub-surface geological zones, where the stream-bed and meander-belt deposits are thickest, (as was earlier indicated under the discussion of the geology of the area). These zones may be, therefore, compared with large buried groundwater channels, with interconnections.

5. CONCLUSIONS

In the past little effort has been made to conduct detailed laboratory studies on subsurface samples and to apply the lab data in the interpretation of the regional geology or to use it in the water resources evaluation studies. Physical properties of sediments, such as grain size, shape, arrangement, size distribution, degree of sorting and compaction determine the size and shape of the intergranular openings or pore spaces, and the latter, in a large measure, control the hydraulic properties of the sediments. On the other hand, the above mentioned properties of sediments are a direct function of the geological processes and environments, under which the sediments originated and were subsequently deposited. A study of the physical properties of the sediments in the laboratory, therefore, provides a direct link between the geology and the hydrology of the groundwater aquifer. It provides much useful information and aditional evidences to corroborate and supplement the geological and hydrological field studies.

Studies in Rechna doab clearly demonstrate the value of using the field as well as the laboratory techniques in the water resources investigations. These studies also suggest that the laboratory data may be profitably used to determine important hydrologic properties of the aquifers such as coefficients of permeability, transmissibility and storage. These are the more significient hydraulic characteristics and the knowledge of these values enables quantitative estimation of the available groundwater and makes it possible to predict the hydraulic behaviour of the aquifer tapped under a given set of withdrawal conditions.

6. ACKNOWLEDGEMENT

Authors thanks are due to Mr. Saiyyid Hamid, Deputy Chief Engineer, Wapda, for the facilities provided during the course of the investigations, to Dr. A.G. Asghar, Director, Department of Land Reclamation, Lahore, in whose laboratory, the samples were tested and to Dr. N.M. Khan, Deputy Director General, Bureau of Mineral Resources, Geological Survey, for the permission to contribute this paper to this Symposium.

REFERENCES

HERON, A.M., 1913. "The Kirana and other Hills in the Chaj and Rechna Doabs." *Rec.Geol. Surv. India*, Vol. XLIII.

KAZMI, A.H., 1959. "Report on the Geology and Ground-water Investigations in Rechna Doab, West Pakistan." *Geol. Surv. of Pakistan*, Admin. Rep. 25.

TIPTON & KALMBACH Inc., 1959. "A Review of Project Number One — Salinity Control Program in West Pakistan." (Report to West Pakistan Water and Power Development Authority).

WAPDA, 1959. "Report on Salinity Control and Reclammation Project Number One." West Pakistan Water and Power Development Authority.

WAYS OF INCREASE OF EXPLOITATION UNDERGROUND WATER RESOURCES (SUPPLIES)

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ABSTRACT

1. By the term exploitation underground water resources we mean the expenditure of the latter that can be obtained by water-collecting constructions having suitable technical and economic properties at the given exploitation rate, the quality of water being up to the requirements during the whole exploitation period estimated.

2. The increase of exploitation resources in suitable conditions can be obtained by:

a) the increase of the regulating capacity of the aquifer in the water-collecting area.

b) the increase of the lowering of the water level in exploitation.

c) the shortening of the distance between the water-collecting and the feeding areas.

d) a good choice of the water-collecting area with the best filtering properties of the aquifer and with its greater thickness.

e) the increase and more even feeding of the aquifer.

f) the improvement of the water-collecting constructions especially in their water-inlet parts and their arrangements for the decrease of resistance during the water-flow.

g) the use of deeper water-lifting pumps and rationalization of the self-flow.

h) the decrease of the expenditure elements of the aquifer balance.

3. The increase of the exploitation resources should correspond to the requirements as to the quality of water and technical and economic indices.

By the term "exploitation underground water resources (supplies)" we mean the expenditure that can be achieved by water-collecting constructions having suitable technical and economic properties at the given exploitation rate, quality of water being up to the requirements during the whole exploitation period estimated.

At present in some areas especially in arid ones there is a great need of water. Therefore the increase of exploitation underground water resources is a vital question nowadays.

Such increase of exploitation underground water resources is determined firstly by a set of natural hydrogeologic conditions. In some cases such conditions including those of feeding underground water can be changed. The building of captation constructions influencing the expenditure, it is evident that the increase of exploitation resources depends on the technical measures.

One should bear in mind that the exploitation resources must be up to the requirement so far as the quality of water is concerned. Therefore when exploitation resources are being increased, the possibility and permissibility of changing the composition of water should be taken into account. For example when drinking water is to be obtained sanitary conditions should be paid special attention to. However it is possible to change the given sanitary conditions for instance by the establishment of sanitary protection zones.

Thus the possibilities of the increase of exploitation underground water resources are determined by natural hydrogeologic conditions, by the possible changes of such conditions by means of technical measures, by the consideration of the requirements as to the quality of water and the means of obtaining water of proper quality and finally by the economic indices.

Allow me to dwell upon the analysis of the principles of the increase of exploitation underground water resources.

In case exploitation underground water resources in natural conditions are limited to their restoration, sometimes it is possible to improve the feeding by the increase of the regulating capacity of underground water by improving the filtering conditions and also by the increase or regulation of the expenditure of the river.

An example of the increase of the regulating capacity of the aquifer is described by professor Plotnikov (1959) in his paper "Estimation of underground water supplies". Suppose we have an aquifer in a river valley in alluvial deposits having but a small thickness (some 5-15 meters). This aquifer is fed by water filtering from the river in which water flows only during high floods that take place at intervals of some 10-20 years. In this case when not only the natural regulating sources but also a part of the ancient. underground water supplies have been made use of we shall have exploitation resources that are dozens and hundreds of times greater than the natural expenditure of the undeerground flow. In such a case one should get convinced of the increase of supplies greatly exceeding those characteristic of natural conditions by hydrologic analysis of the flow (drainage) of the river and by the hydrodynamic considerations of the filtering of the river water into the aquifer, the period of high flood being taken into account. When the natural filtration is insufficient it is sometimes improved by providing filtering ditches. When the period of filtering is not long enough. the surface flow (drainage) should be regulated.

When the exploitation underground water resources are limited to the capacity of the underground flow (the product of the coefficient of filtering multiplied by section of the underground flow) the main way is the increase of its hydraulic inclination by either lowering the levels of the water collecting area or by shortening the distance between the watercollecting and the feeding area of the aquifer or by both the ways simultaneously.

In the book "Estimation of underground water resources" (1959) Professor Plotnikow described a case of water-collection in the pressure underground flow in the alluvial deposits in a river valley of relatively small width. In the paper it is shown that the steeper the hydraulic inclination is in the upper part of the underground flow from the water-collecting area, the greater the exploitation resources are. The increase of hydraulic inclination is achieved by the additional lowering of the level in the underground flow in the water-collecting area or by the foundation of the water collection closer to the feeding area. The possibilities of the increase of the aquifer feeding should be taken into account; when the feeding is uneven the sufficiency of the regulating capacity of the water aquifer as well as the decrease of the hydraulic inclination during the period when deefing is missing should be checked up and controlled.

In a number of cases the exploitation underground resources are limited to the yield of separate boring wells (Mining shafts) as well as the series of wells at the permissible lowering of the level in captations. In this case the increase of exploitation underground water resources can be achieved by a good choice of the water-collecting area with the best filtering properties of the water aquifer and its highest thickness and also by a good choice of the design of the well especially in this water-inlet part (filter) and by the arrangement of the wells. All this is meant for the decrease of the resistance of the underground water when it flows on its way to the area of the wells and in the wells themselves. Besides the increase of the yield with the corresponding of the lovel is made possible by the use of deeper waterlifting pumps when needed, technical and economic requirements should not be overlooked. In case there isa self-flow in the well sometimes technical rationalizing is possible to increase the yield, especially when the well is of the gas-lifting type. This can be achieved sometimes by a letter choice of water-lifting pipe diameter.

The increase of the water permeability of a certain layer i.e. the product of the mean coefficient of filtering by the thickness of the aquifer in the water-collecting area, proportionally decreases the lowering of the water-level in the wells at the expense of the resistance when underground water flows to the wells in the water-collecting area. Here is meant the constant yield of the wells, their number and arrangement. When the aquifer areas are less than 500-1000 km; the resistance of water on its way in the water-collecting area presents a considerable value compared to the resistance in the aquifer area as a whole; therefore with the same lowering in the water-collecting areas with high water permeabilty the increase of the yield of the wells will be considerable.

Besides the ways of the increase of the exploitation water resources we spoke about some other ways are possible such as the obtaining of artificial underground waters the decrease of the expenditure element of the underground water balance and also the transpiration of plants and evaporation from the surface of the soil when the underground water levels are lowered.

Thus the increase of the exploitation underground water resources is accomplished by:

1. a good choice of water collecting areas with the best filtering properties and the decrease of resistances of underground water in the wells.
2. the increase of the regulating capacity of the aquifer.
3. the better feeding of the aquifer.
4. the increase of the lowering of the water level in exploitation and shortening the distance between the water-collecting and feeding areas of underground water.
5. the decrease of the expenditure part of underground water balance (transpiration of plants, evaporation from the soil etc.)
6. a good choice of the water lifting pump including rationalization of the self-flow.

WAYS TO INCREASE EFFICIENCY OF EXPLORATION WELLS

Dr. Friederich NORING, Wiesbaden

1) It is important to collect data concerning groundwater levels and chemistry, also of precipitation and surface runoff, before commencement of drilling. It is necessary to relate all data with sea level or another uniform base.

2) It seems profitable to renounce stiff drilling programs. It is rather better to settle each new borehole after making full use of the results of the preceding exploration well.

3) Therefore the permanent of frequent presence of an consulting hydrogeologist is advantageous.

4) Also the principal composition of water samples should be examined with in the exploration field.

5) In unknown regions three steps of investigation should be divided, 1. to recognize the different strata and aquifers, 2. to examine the aquifers of great promise by pumping tests, 3. to build finally production wells.

6) By this way rotary and dry drilling can be used combined after necessity.

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GROUND WATER IN THE ARID AND SEMIARID ZONE; ITS SOURCE, DEVELOPMENT, AND MANAGEMENT (1)

C. S. CONOVER (2)

ABSTRACT

Ground water in arid and semiarid areas is governed by the same geologic and hydrologic controls as in humid areas. However, the meager and variable precipitation and the high evapotranspiration rate in these areas exert a profound influence upon the accumulation and replenishment of ground water. The extreme variability in precipitation must be recognized for a proper understanding of recharge of ground water in arid areas, as this variability is responsible for the existence of water in the aquifers in these areas. Significant recharge occurs during and after infrequent periods of heavy precipitation and to a significant degree by concentration of runoff. In essence, as far as recharge is concerned, the frequency and intensity of wet years is more significant than the frequency and length of periods of drought.

Optimum development, management, and control of ground water in water-deficient arid and semiarid areas requires special philosophical and economic considerations as well as the understanding and application of hydrogeologic principles. Successful long-term development and management of ground water in these areas must recognize and be tailored to two main situations: (1) in areas where the volume of ground water in storage is large and the recharge meager, ground water must be mined, (2) in stream valleys where the ground and surface waters are intimately related, the two must be utilized as a unit water resource on a perennial basis.

Mining of ground water can be managed on a planned-life basis for aquifers of small volume or thickness or on the basis of an economic rate of decline of the water levels in aquifers of large volume or thickness. Effective management of aquifer development depends upon adequate spacing of conservatively pumped wells.

RÉSUMÉ

L'eau souterraine des régions arides et semi-arides est gouvernée par les mêmes principes géologiques et hydrologiques que ceux régissant les régions humides.

Cependant, les précipitations faibles et variables et la grande importance de l'evaporation dans ces régions exercent une grande influence sur l'accumulation et sur l'alimentation de l'eau souterraine. Il faut insister sur la variabilité extrême des précipitations pour comprendre proprement la réalimentation des eaux souterraines des régions arides, parce que cette variabilité est à la base de l'existence de l'eau des nappes. La réalimentation effective se produit pendant et après les rares périodes de grande précipitation et en quelque sorte du fait de la concentration de l'écoulement. En effet, au sujet de la réalimentation, la fréquence et l'intensité des années humides sont plus significatives que la fréquence et la durée des périodes d'aridité.

1. INTRODUCTION

Ground water in arid and semiarid areas is subject to the same geologic controls and to the same hydrologic principles as ground water in humid areas. Ground water is a phase of the hydrologic cycle in either case. Thus locating, evaluating, developing utilizing, and managing ground water in arid and semiarid areas are essentially a matter of applying basic principles to environmental conditions peculiar to these areas. Not only must special environmental conditions be dealt with, but certain hydrologic factors such as coefficients of storage and transmissibility and rate of evapotranspiration assume special importance. Time likewise assumes special importance. Further, optimum development, management, and control of ground water in waterdeficient arid and semiarid areas requires special philosophical considerations as well as the application of hydrogeologic principles.

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(1) Publication authorized by the Director, U.S. Geological Survey

(2) Assistant Chief, Ground Water Branch

2. THE ARID AND SEMIARID ZONE

The arid and semiarid zone (or areas) may be described on the bases of climate, soil, vegetation, animal distribution, or land use. However, climate is the basic controlling element of the arid zone and therefore, for hydrologic considerations is the logical factor by which to describe these areas.

The climate of the arid and semiarid areas is generally characterized by relatively high temperatures and low humidity and consequently by high potential rates of evaporation. The arid and semiarid areas may be described simply as areas where water deficiency is large compared with need.

A large part of the western United States is in the water-deficient area. Large segments of the population are migrating to the Southwestern States. The large per capita use of water in the Southwest, due in large part to irrigation, coupled with the increase in population, presents problems in development and management of ground water and necessitates full understanding of its source and other hydrologic characteristics.

3. GROUND-WATER RECHARGE

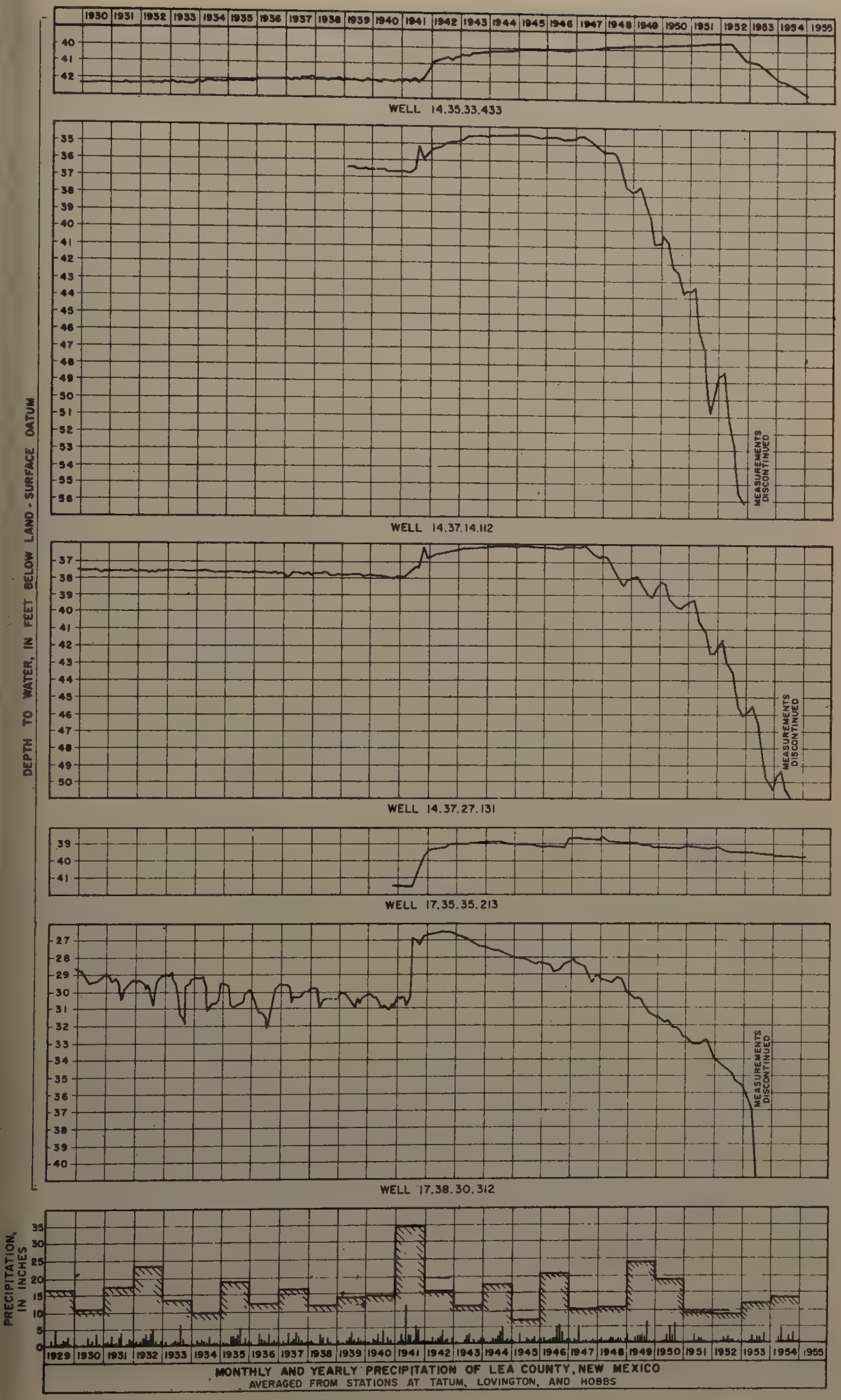
Precipitation, the source of our usable ground water, is on the average only about 20 inches per year in the arid and semiarid areas of the United States. It is higher in the mountains and much lower in the lowlands. Runoff is less than 1 inch in most of this area.

The low precipitation and high evaporation pose the questions of «How is ground water recharged and how much recharge is there?» The key, to a great extent, lies in the extreme variability of precipitation. The mean rainfall does not represent the rainfall that might be expected each year. Most years have precipitation less than the long-term average. Precipitation during the year likewise generally follows a pattern of long dry spells punctuated by occasional short periods of heavy rainfall. A large percentage of the rainfall for a year may occur in one or a few intense storms.

During the periods of average and below-average precipitation in the arid and semiarid areas, the low humidity and consequent high evaporation take their toll of the soil moisture. After a long dry spell, drying of the surficial deposits extends to a depth of several feet.

It is evident then that appreciable water is required to provide moisture below the roots of plants and the zone of surface drying. Significant quantities of water to effect recharge come about in two ways: (*a*) the intense storms that occur occasionally during most years, when runoff concentrates in the drainage ways to provide excess water for recharge; and (*b*) the excess precipitation in frequent years which provides opportunity for direct recharge from the ground surface to the water table.

The infrequency of recharge in the semiarid area is illustrated by the fluctuations of water levels in wells on the High Plains in northern Lea County, New Mexico. The High Plains are characterized by the absence of streams and the existence of numerous closed shallow depressions. Water levels have been recorded in this part of the High Plains since late 1929. Figure 1 shows the fluctuations of water levels



-- Graphs showing fluctuations of water levels in five representative wells, and precipitation in Lea County, N. Mex., 1929-1954.

in 5 wells from 1930 to 1955. During the early period of record the 4 upper wells were many miles distant from heavily pumped irrigation wells that now are common on the High Plains. The fluctuations in water levels in these 4 wells until about 1947 are essentially a reflection of natural effects—that is, intermittent recharge and continuous ground-water discharge to the southeast.

The average annual precipitation in this part of the High Plains in New Mexico is about 15 inches. From 1930 to 1941 the annual precipitation ranged from a maximum of 23 inches in 1932 to a minimum of 10 inches in 1934. In no year prior to 1941 was there a marked rise in water level, though small rises occurred after some heavy storms. However, correlation of rises in water level with the amount of precipitation in individual storms is imperfect, as antecedent periods of precipitation and the intensity and distribution of the storms are important but unknown factors. The local geologic and hydrologic setting of individual wells also is imperfectly known.

Precipitation in 1941 was appreciably above normal throughout most of the Southwest and, on the High Plains in New Mexico, in the vicinity of the wells in question, was 35 inches, more than twice normal. Water levels began rising in late May 1941, within a week after the heavy rains began. Precipitation in May 1941 exceeded 13 inches, nearly equaling that for a normal full year. Heavy rains occurred also in September and October 1941. The average rise in water level in 1941 beneath the High Plains in New Mexico was 2.4 feet. The maximum observed rise was 8.6 feet in a well west of Tatum, New Mexico, where during the entire previous 11-year record the water level had declined almost continuously at a rate of about 0.1 foot a year.

Note that recharge to the water body, as evidenced by the rise in water levels shown in the upper curve, figure 1, continued for a number of years after 1941, even though precipitation in 1942-45 was only about normal. Though some of this rise may be due to slow downward percolation of 1941 recharge, the explanation for most of the rise seems to be that once the material in the zone of aeration becomes saturated, recharge is facilitated from average or above-average storms.

Hydrographs of water levels in wells on the High Plains illustrate that even in the semiarid areas, with an annual precipitation of 15 to 18 inches, significant recharge occurs only during and after years when precipitation is appreciably above normal. Such years are infrequent. In more arid areas, such as the southwestern part of New Mexico where precipitation is less than 10 inches per year, recharge must occur even less frequently. Thus, so far as recharge is concerned, the frequency and intensity of wet years are more significant than the frequency and length of periods of drought.

3.1. *Amount of recharge*

Inasmuch as recharge occurs infrequently in the arid and semiarid areas, the next question is «How much is the recharge?» Recharge seldom can be measured directly; even if it could, to be meaningful a long-term average over the entire recharge area of an aquifer would be needed. Because of the impracticality of measuring recharge directly, other measures are normally employed to determine recharge. This can be done by measuring the natural discharge from an aquifer, such as represented by springs or low flow of streams, or by determining the flow of water through the aquifer. The flow of water through and discharge from an aquifer are essentially constant and adjusted to the average recharge, whereas recharge itself is intermittent.

The average recharge to the High Plains in northern Lea County, New Mexico, can be estimated by calculating the ground-water flow past Lovington. The 3,850-foot contour of the water table through Lovington is 45 miles in length. The slope of the water table averages about 15 feet per mile along this contour. With a contributing area of 1,200 square miles and a coefficient of transmissibility of approximately 100,000 gallons per day per foot, an average recharge rate of about 1 inch per year is indicated. Though this rate is subject to refinement it does show the small amount of recharge. It is of interest to note that, in 1941, the average rise of water level of 2.4 feet under the Lea County portion of the High Plains was equivalent to recharge of nearly 6 inches, assuming a coefficient of storage of 0.2. That is, the recharge in 1941 equaled 6 years of average recharge. However, the expected frequency of such heavy precipitation is probably on the order of once every 100 years or so.

The recharge potential of the High Plains is comparatively large for arid-semiarid areas because of the absence of through-flowing streams, the existence of closed depressions where surface runoff accumulates, and the average annual precipitation of more than 15 inches. Direct recharge from precipitation in other arid-semiarid areas therefore is probably smaller on the average. Recharge derived from streams is a different matter, as will be discussed later.

4. Development and management of ground water

The small rate of recharge to aquifers in the arid and semiarid areas poses questions in the development and management of ground water. Many aquifers may be classified with respect to development and management into two broad categories (Conover, 1961), (*a*) those which have large storage but negligible recharge and which are not intimately related to streams, and (*b*) those associated with streams.

By proper management, a dependable supply of water of acceptable quality can be developed on a virtually perennial basis from aquifers of the second category—that is, those associated with streams. Aquifers of the first category can yield only a small perennial supply once their storage is depleted, and therefore the ground water must be mined. Mining of ground water can be managed on the basis of (*a*) a planned life for aquifers of small volume or thickness or on (*b*) a planned rate of water-level lowering (depletion) for aquifers of large volume or thickness.

4.1. *Ground-water Mining*

Consider the case of the High Plains of Lea County, New Mexico, as a type problem of developing and managing an aquifer of the first category having a small thickness but large areal extent. The surficial Ogallala formation of Tertiary age is the water-bearing formation. It is floored by nearly impervious shales of Triassic age. Figure 2 shows the saturated thickness of the Ogallala. Computations made from this map using an assumed storage coefficient of 0.2 indicate that about 25,000,000 acre-feet of recoverable water was in storage in 1953. The average rate of recharge is on the order of 50,000 acre-feet a year. Thus, the water in storage represents more than 500 years of recharge. If development of water were limited to the recharge, of what value would be the water in storage? To complicate the picture, the water in the aquifer is not in dead storage but for the most part is moving southeastward through the aquifer into Texas, at a rate equal to the recharge and eventually is discharged at the edge of the High Plains some hundreds of miles to the east. Pumping of water in Lea County cannot stop the natural discharge. Thus, even if development of water were limited to the rate of recharge, the water actually would be taken from storage, would not be a perennial supply, and would utilize only a small part of the water in storage.

Figure 3 shows contours of decline of water levels in the Lea County, New Mexico, portion of the High Plains in the period from January 1950 to January 1955. During this period about 90,000 acres were irrigated each year and a total of nearly

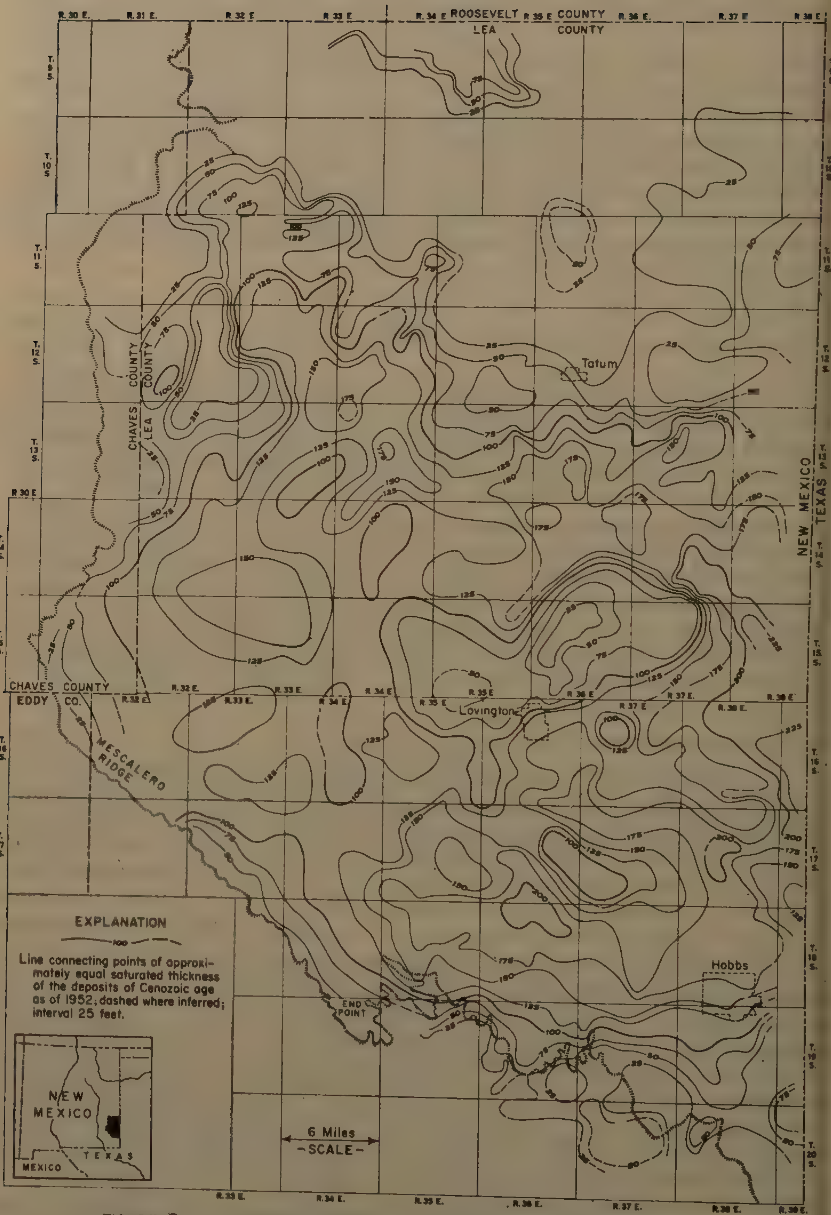
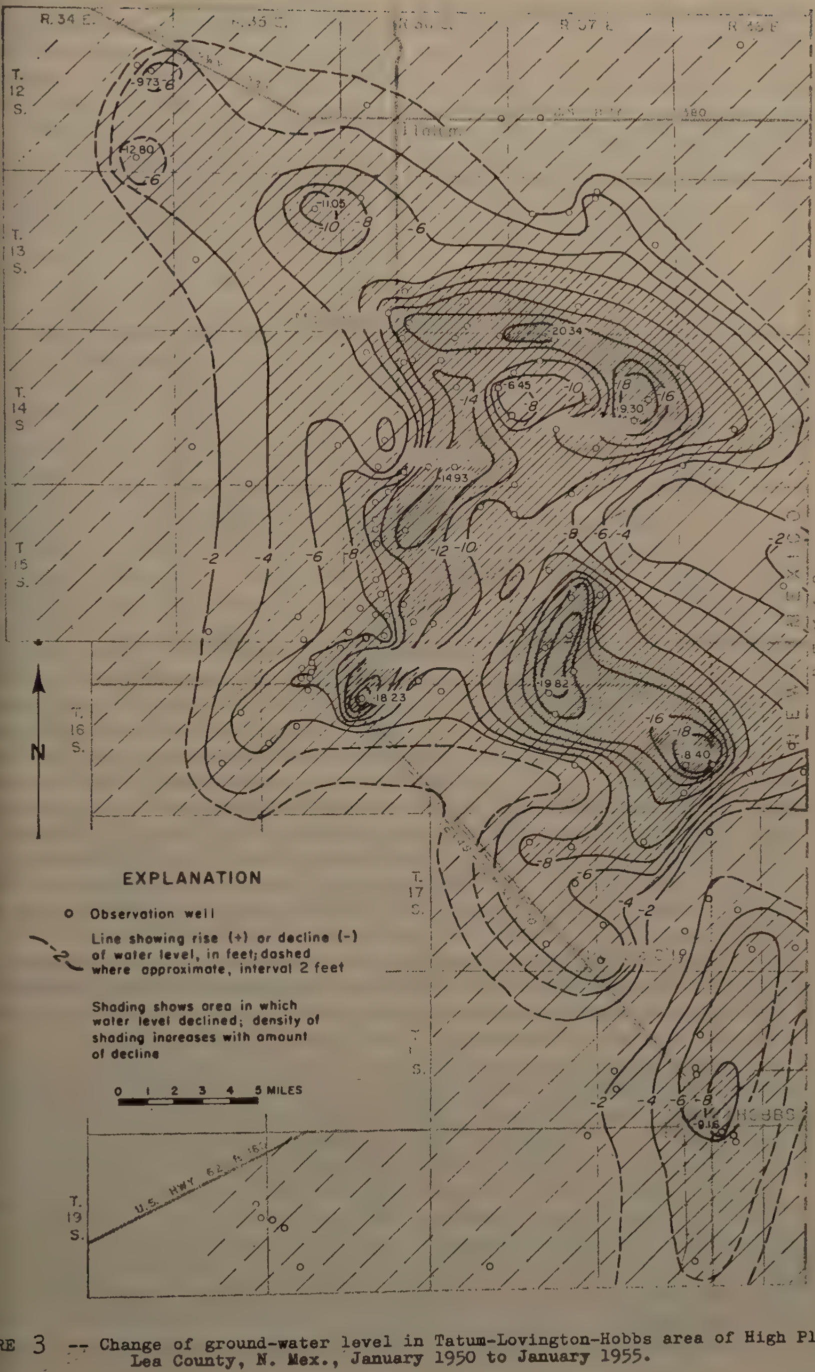


FIGURE 2 MAP SHOWING THICKNESS OF THE ZONE OF SATURATION IN THE OGALLALA FORMATION IN NORTHERN LEA COUNTY, N. MEX.



GURE 3 -- Change of ground-water level in Tatum-Lovington-Hobbs area of High Plains, Lea County, N. Mex., January 1950 to January 1955.

three-fourths of a million acre-feet of water was pumped. The map shows the broad coalescing of the cones of depression created by pumping of the irrigation wells. The irrigation is not uniformly distributed because of the variable character of the land. The areas of large decline reflect the areas of heavy concentration of pumpage. The map shows six areas under which the lowering of water level exceeded 3 feet per year, nearly 20 feet in 5 years in the six areas. The map shows also that the effects of pumping have spread many miles from the center of pumping but at the same time the major effects of pumping have been confined to the areas of heavy pumping. This illustrates two main principles for effective management of aquifer developments in areas of mining: (*a*) wells must be spaced to develop water throughout an aquifer and (*b*) pumping should be at a rate small enough to allow water to move to the centers of pumping from the water-table divides between wells. Simply stated, when water is pumped from storage in a thin aquifer, such as the Ogallala, the development should be limited and orderly to allow more water to drain into the pumped areas from surrounding areas not suited to development, and to lengthen the life of the reservoir to a period acceptable from a broad economic and sociologic viewpoint. The time must be great enough to allow for orderly amortization of equipment, of public works, and of other development associated with a normal economic community, as well as for the creation of wealth over and above the costs of developemnt, as with other mineral resources. The State Engineer of New Mexico, after consideration of many aspects, set 40 years as the optimum minimum life for agriculture of the ground-water resource in the High Plains of Lea County. In essence, water rights are granted, in each township, equal to the volume of extractable water in storage under the township divided by 40. This type of regulation incorporates the two prime hydrologic factors, (*a*) well spacing and (*b*) time, that are requisite to optimum development of ground-water storage. Such farsighted regulation is unique and the wisdom of such regulation will probably become more evident and widely accepted as time elapses. This system of regulation does not mean that the water actually will be exhausted in that time. It assures a stable development and economy, provides for the time needed to investigate and institute conservation and rectification measures that might be undertaken to sustain the economy that develops. Such measures may include substitution of low-water-requirement industry for high-water-requirement crops, planting of low-water-requirement crops, improved efficiencies of irrigation methods to conserve water, and initiation of artificial-recharge measures.

What about development and management of ground-water storage where the aquifer is of considerable depth, as opposed to the Ogallala of the High Plains where the shallow base puts a restriction on the lowering of the water level?

The Animas Valley in southwestern New Mexico (Reeder, 1957) is selected to illustrate this situation. The Animas Valley is an intermontane basin rather typical of the Basin and Range province of the arid and semiarid Souht-west, with the special features that pumping of ground water has been regulated almost from the beginning of development and that study of the hydrologic factors has been carried on concurrently with the development. These features are unusual, for regulation of development and initiation of hydrologic studies usually come about after development has progressed to the stage that the supply has been substantially reduced or water levels are lowering at such a rate as to cause concern regarding the future of the water supply.

Animas Valley is a closed topographic basin in the extreme southwestern part of New Mexico, southwest of Lordsburg. The valley floor slopes northward with an average gradient of 23 feet per mile in the southern part and 11 feet per mile in the northern part. The northern part, known as the lower Animas Valley, is nearly level, about 5 miles wide and about 25 miles long. Irrigation with ground water is practiced in the lower valley.

Lower Animas Valley is bounded on the east and west by northward-trending mountains that rise 1,000 to 2,000 feet above the valley floor. The altitude of the valley floor ranges from about 4,400 feet at Animas to 4,150 feet in the lowest part of the valley 25 miles north. At the northern end near Summit the altitude rises to 4,200 feet, where there is a gentle divide that separates the surface drainage from the Gila River drainage. North Alkali Flat and South Alkali Flat are playas at the north end of lower Animas Valley. The playas are flat and devoid of vegetation. After a heavy rain, water collects on the flats to a depth of a few inches and evaporates. Only occasionally do floodwaters flow northward any great distance through the valley to collect at South Alkali Flat.

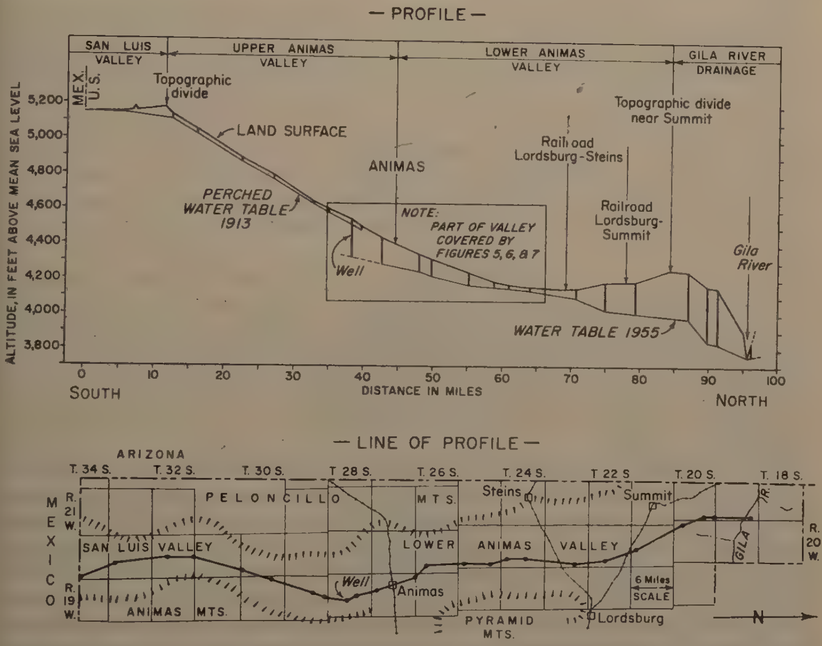


FIGURE 4--PROFILE OF THE WATER TABLE AND GROUND SURFACE FROM THE MEXICAN BORDER THROUGH ANIMAS VALLEY TO THE GILA RIVER, HIDALGO COUNTY, NEW MEXICO

The valley is a graben flanked by igneous masses that form the adjacent highlands to the east and west. The valley sediments have been derived from the highlands after two or more periods of structural activity. The main mass of valley sediments, of appreciable but unknown thickness, is mostly fine grained. The bedrock masses form effective impermeable side-boundaries to the alluvial aquifer system.

Ground water in the Animas Valley occurs in the valley fill, which is composed of beds, lenses, and stringers of clay, silt, sand, and gravel. Locally the ground water is confined, such as where a clay lens extends into the ground-water reservoir. Water-table and artesian conditions grade into one another. Although artesian conditions exist in many places in the valley, at least some of the time, the ground-water reservoir as a whole behaves as a water-table system. Local and temporary artesian conditions add complexities to the interpretation of pumping tests to determine the hydraulic characteristics of the aquifer.

The average annual precipitation during the period of record from 1881 to 1955 was less than 10 inches. Precipitation was below normal in 40 of the 75 years. Only in 4 years was precipitation more than 15 inches, and it was never as much as 20 inches. Fifty to fifty-five percent of the meager annual precipitation in the Animas Valley occurs during the summer months of July, August, and September, when the air temperature and the evaporation rate are high. Precipitation in the highlands, particularly to the south, may be as much as 20 inches a year. Thus, it is evident that, normally, opportunity for direct recharge from rainfall is essentially nil. The principal effect of precipitation in the lower Animas Valley is a reduction in pumping for irrigation with a consequent rise in water level.

Figure 4 is a south-north profile of the ground surface and water table along the axis of the valley from the Mexican border to the Gila River. Note that the ground water flows beneath two surface topographic divides to emerge in the Gila River. Note also that, though South Alkali Flat is the topographic low of lower Animas Valley (just north of the railroad on the profile) the depth to water there is not at a minimum. The main irrigated area extends northward on the profile, from Animas to about where the depth to water is a minimum. Thus, the area of development is 35 to 50 miles from the area of ground-water discharge along the Gila. The contours on the water table in lower Animas Valley show a general northward movement of water.

The flow of ground water down Animas Valley at a particular time is approximately equal to the average rate of recharge over a considerable period of time. The flow past the 4,150-foot contour line in the northern part of lower Animas Valley is computed at 2,700 acre-feet per year. The area of tributary drainage to the 4,150 foot contour line is estimated as about 750 square miles. On this basis the average rate of recharge is less than 0.1 inch per year, less than 1 percent of the annual normal precipitation of 10 inches.

The irrigated area in Animas Valley in 1955 is shown by figure 5. During 1955, 11,400 acres were irrigated with 19,800 acre-feet of water pumped from 127 irrigation wells. The irrigated acreage has increased each year since 1948, when 1,000 acres were irrigated. The total water pumped for irrigation from 1948 through 1955 was about 115,000 acre-feet. As the irrigation wells in Animas Valley are 35 to 50 miles from the natural discharge area of the aquifer, none of the natural discharge of about 2,700 acre-feet per year has been, nor can be, diverted to the pumps in the foreseeable future. Thus the water pumped has come from ground-water storage and water levels decline from year to year.

The decline of water level that occurred from April 1948 to January 1955 in the lower Animas Valley is shown by figure 6. The contours of decline are a measure of the diminution in ground-water storage that took place in the 7 years. The maximum decline was more than 25 feet under a 2-square-mile area centered around sec. 3, T. 26 S, R.20 W. The area of maximum decline coincides with the computed center of concentration of pumpage, though no irrigation well existed in sec. 3. In 1955, two-fifths of the used irrigation wells were within a 2-mile radius of this center of pumpage.

The coefficient of transmissibility of the aquifer was determined from pumping tests to be on the order of 50,000 gallons per day per foot. As pseudo-artesian conditions exist for short periods of pumping, and as it was evident from seasonal changes in water level that essentially water-table conditions existed, the coefficient of storage was determined, year by year and for periods of several years, by equating the volume

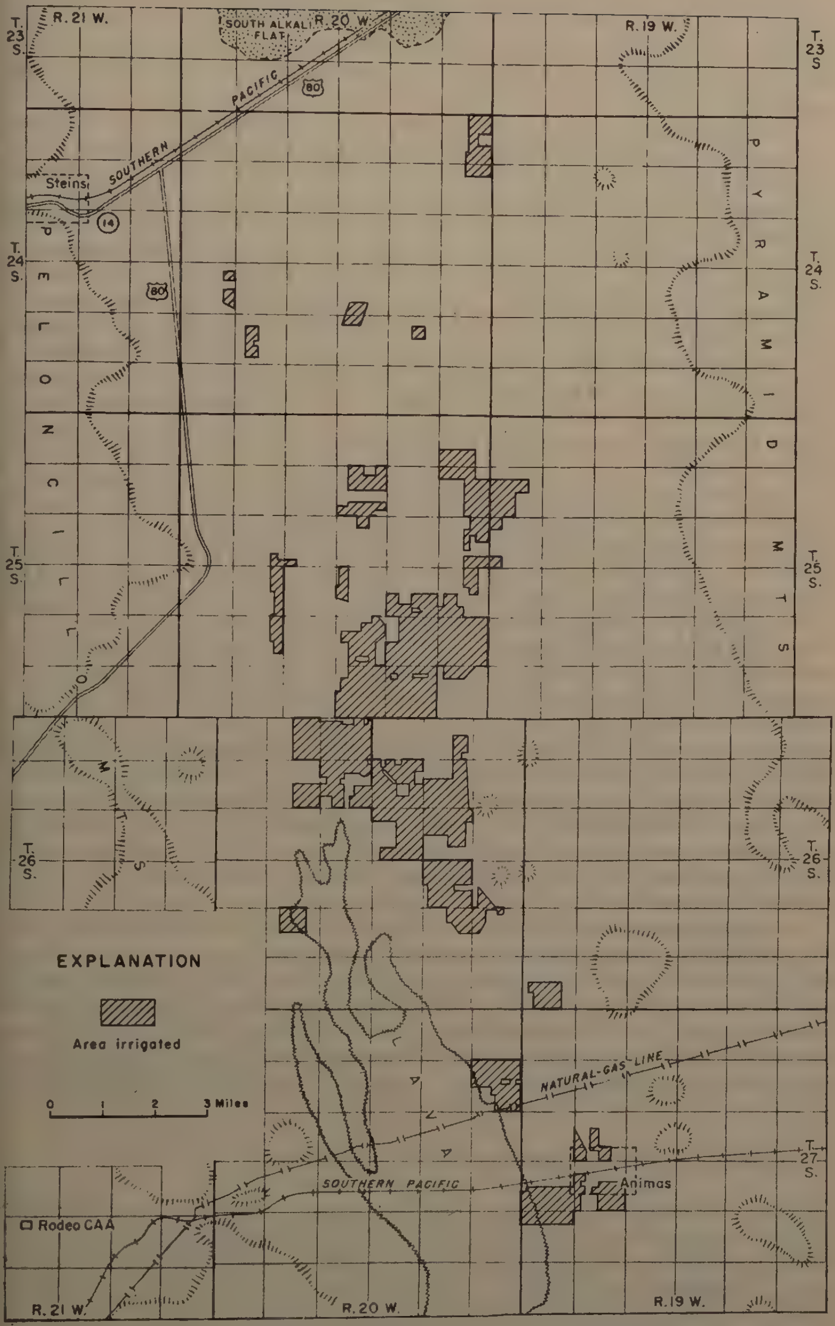


FIGURE 5 Areas irrigated in 1955 with water from wells in Animas Valley, Hidalgo County, N. Mex.

of sediments dewatered with the volume of water pumped. The coefficient of storage so determined averaged 0.1. For example, in the period April 1948 to January 1955, the volume of sediments dewatered as shown in figure 6 was about 1,180,000 acre-feet. As 115,000 acre-feet of water was pumped in this period, the coefficient of storage equals 0.1.

Intense interest in irrigation with ground water in the Animas Valley developed in the spring of 1948. Though ground water had been known to exist in the valley since before World War I and at times the State had sought to promote interest in development of the water, only 1,000 acres had been irrigated in 1947. However, because of the strong speculative interest in irrigation early in 1948, the State Engineer of New Mexico declared the Valley a «Ground Water Basin,» thereby setting in motion the procedure of applying for and developing water rights. The interest in development in 1948 was such that, by June 1948, 100 permits had been issued to irrigate 14,200 acres. The area was forthwith closed by the State Engineer to further appropriation. Actual development of irrigation wells proceeded at a slower pace. By 1955, 11,400 acres, 82 percent of that permitted, had been placed in cultivation. Thus, the lowering of water level from 1949 to 1955 of a maximum of more than 4 feet a year was caused by irrigation development averaging not more than 50 percent of that permitted.

Optimum regulation of ground-water development in the lower Animas Valley was facilitated by projecting rates of water-level declines into the future. As a step in forecasting the effects of development, theoretical computations of declines of water levels in the Animas Valley were made for the period 1948 to 1958 and compared with actual declines to test the validity of the geohydrologic parameters. Computation of the theoretical lowering was accomplished basically by use of the Theis (1935) nonequilibrium formula. It was assumed that each existing irrigation well was pumped at a constant rate equivalent to 2 feet of water a year upon the acreage permitted for irrigation from the particular well. The previously determined coefficients of transmissibility and storage were used to compute the declines of water level on a 3-mile grid in the Valley. The effects of the valley boundaries were computed by the method of image wells. The total decline at each 3-mile grid point was calculated by summing the declines caused by each individual well and image well. Figure 7 shows the computed decline of water level for the 10-year period 1948-58. A maximum decline of 35 feet under about 6 square miles, averaging 3.5 feet per year, is indicated. Note the close agreement with the pattern of actual declines measured from 1948 to 1955 as shown in figure 6.

Further computations for the period 10 to 20 years (1958-68) indicate that with full permitted development in the second 10 years, a total decline of 65 to 70 feet can be expected in the center of the irrigated area. Thus, the long-term decline of about 3 feet per year in the center of the irrigated area is such that the irrigators are assured of water for the foreseeable future, and they generally will be able to afford the gradually increased pumping costs occasioned by the increased pumping lift by making the necessary improvements in farming practices and by other measures.

4.2. AQUIFERS ASSOCIATED WITH STREAMS

Consider next the development and management of aquifers associated with streams in the arid-semiarid areas. Development can be perennial if the net consumptive use of water does not exceed the sum of (*a*) natural discharge stopped and (*b*) recharge induced or increased, by virtue of the development or by other artificial means. The prime requisites for perennial development are (*a*) the location and character of the discharge areas must be such that pumping of wells can effectively

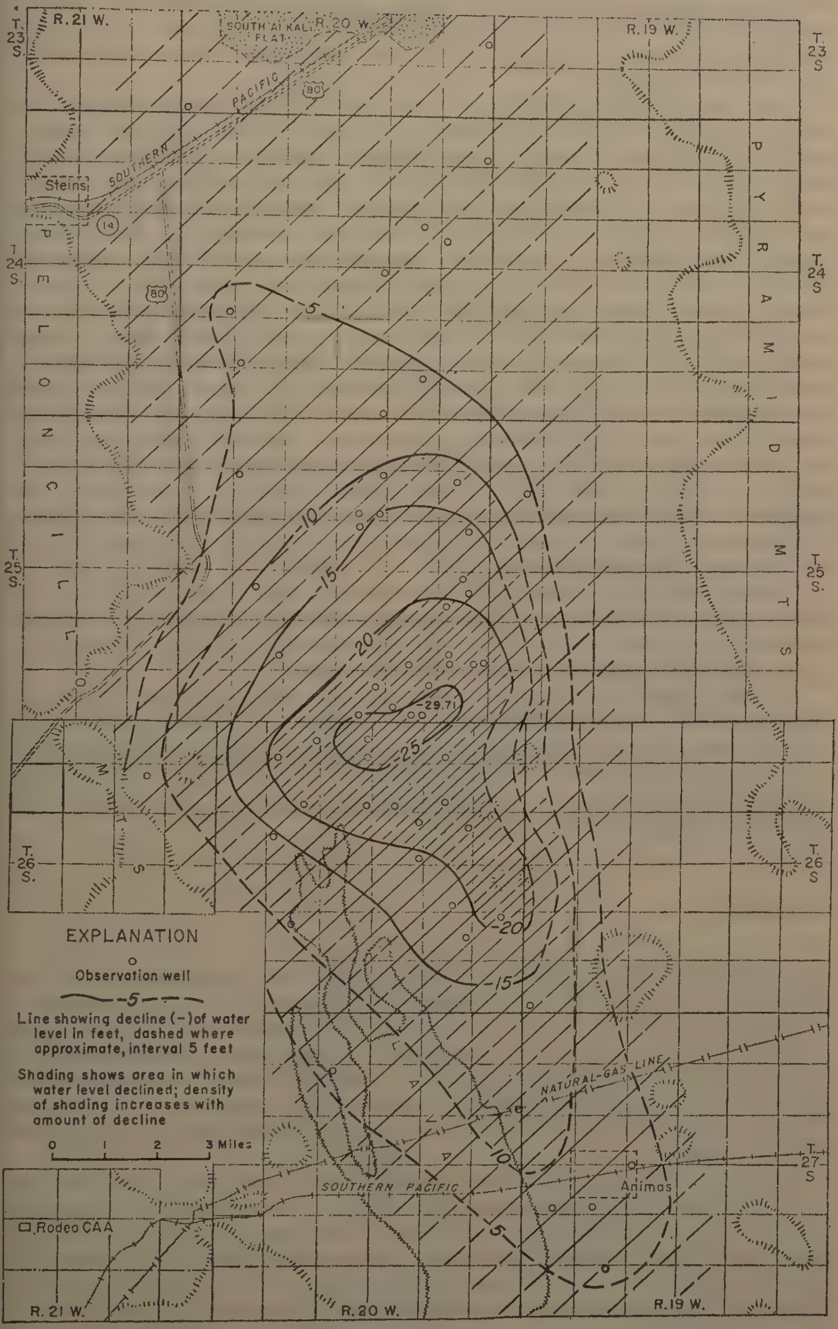


Figure 6. Decline of ground-water level from April 1948 to January 1955, lower Animas Valley, Hidalgo County, N. Mex.

reduce the natural discharge from the aquifer, and (or) (*b*) recharge to the aquifer can be increased in the recharge area or induced in the discharge area. Ground-water reservoirs in alluvial valleys wherein the surface and ground waters are intimately related fit this category.

The amount of water available for net consumptive use on a perennial basis in aquifers associated with streams in arid and semiarid areas is essentially equal to the difference between the inflow, primarily that brought in by the stream, and the outflow that must be allowed by virtue of prior water needs and rights downstream and by the necessity of maintaining salt balance. In many valleys the gross consumptive use of water exceeds the beneficial consumptive use because of areas of native phreatophytes. Streamflow is occasionally inadequate for needs in spite of regulation by surface reservoirs. However, the alluvial aquifers remain full and wells can be installed. Usually, wells are installed by individuals either to supplement inadequate surface supplies or to develop water where there is no right to surface water. As these wells commonly are located at a spot convenient to where the water is to be used, evapotranspiration by native vegetation may be reduced little, if any, by the pumping and the net consumption of water thus may be increased. This extra water consumption results in a decrease in ground storage, with consequent increased depletion of streamflow downstream and further incentive for installation of more wells. This cycle of events may reach the point that the stream is dried up except for flood flows. This unplanned though somewhat effective use of the ground-water reservoir in conjunction with the surface stream benefits those who have wells but works a hardship on those who have only surface-water rights.

Planned development and management of ground water in streams or valleys can increase the available water supply by salvaging nonbeneficial losses in areas of shallow water and will facilitate using the ground-water reservoirs in conjunction with the surface supply to the maximum benefit of all water users.

A fully managed ground-water and surface-water supply with properly located and spaced wells not only will maintain but will increase the firm supply because of (*a*) the savings in evaporation resulting from storing surface waters underground, (*b*) the capture of floodwaters by surface reservoirs made vacant by storing water underground, (*c*) the reduction of evapotranspiration losses by phreatophytes, and (*d*) the recirculation of water by pumping.

5. SUMMARY

In summary, ground water in arid and semiarid areas is governed by the same geologic and hydrologic principles as in humid areas. However, the climate, particularly the meager and variable precipitation and the high evapotranspiration rate, exert a profound influence upon the accumulation and replenishment of ground water. Significant recharge occurs during and after infrequent periods of heavy precipitation. Recharge occurs, to a significant degree, by concentration of surface runoff. Recharge on the average, areawise and timewise, is small compared with the development and need for water.

Successful long-term development and management of ground water in the arid and semiarid areas must recognize and be tailored to two main situations: (*a*) in areas where the volume of ground water in storage is large and the recharge is meager, ground water must be mined; (*b*) in stream valleys where the ground and surface waters are intimately related, the two should be utilized as a unit water resource on a perennial basis. In both situations, the tendency for increased salinization of the waters, though not discussed here, must be recognized as a problem to be faced.

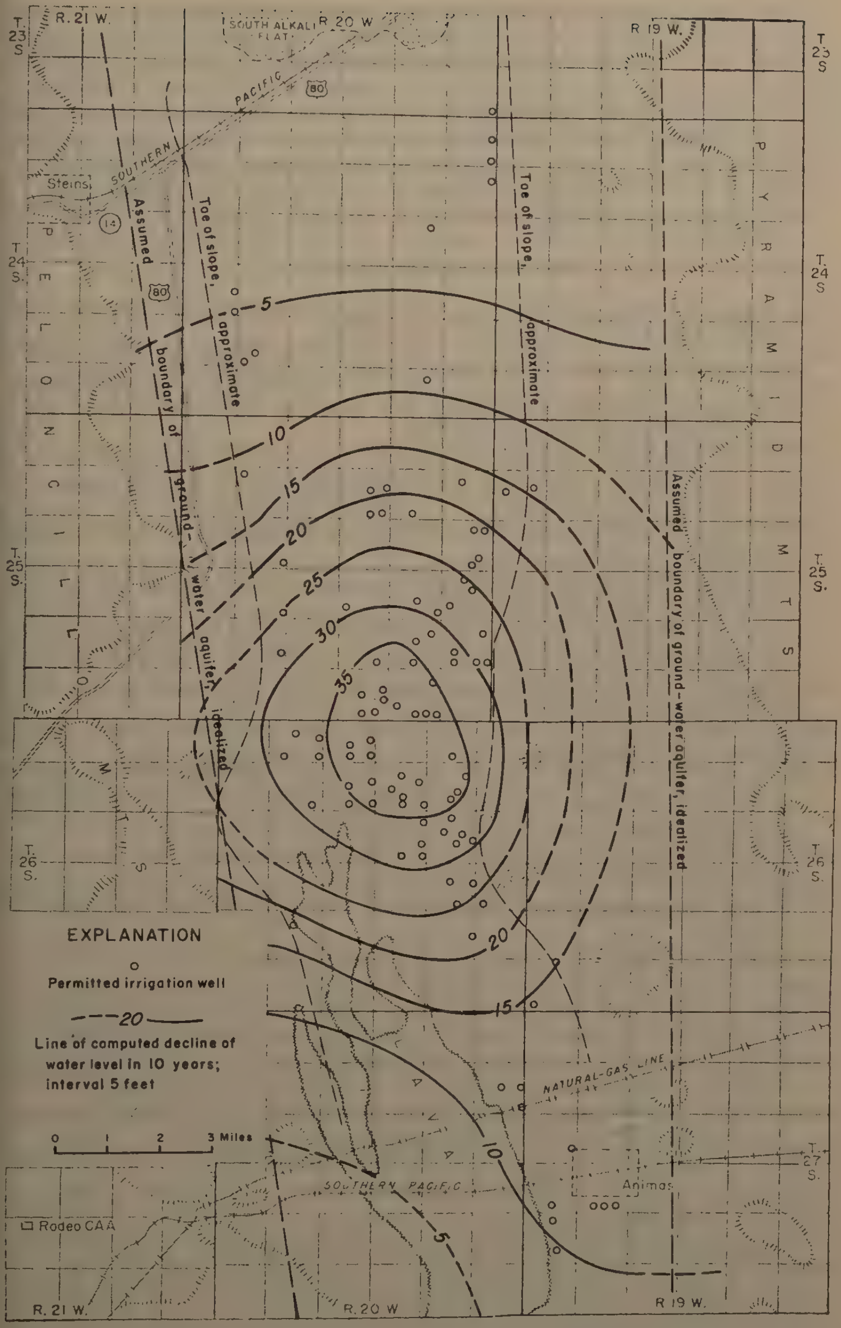


FIGURE 7 Computed lowering of the water level in 10 years (1948-58), lower Animas Valley, Hidalgo County, N. Mex. (Estimated pumpage based on irrigation permits as of 1950 and actual pumpage for 1948 to 1955.)

Permanent occupation of the arid and semiarid areas requires (*a*) improved efficiencies of all uses of water to reduce losses, pollution, and salinization, (*b*) substitution of low unit per capita water development, such as industry, for high per capita water development as represented by agriculture, (*c*) increased utilization of saline waters, such as for industrial processes, (*d*) conversion of saline waters to fresh waters, (*e*) increased recharge where geologic and hydrologic conditions are favorable, and (*f*) importation of water from areas of water surplus. Weather modification ultimately may play a significant role, though this has yet to be demonstrated.

SELECTED REFERENCES

Ash, Sidney R., 1961, Ground-water conditions in northern Lea County, New Mexico: *U.S. Geol. Survey open-file rept.*, 48 p.

Conkling, Harold, 1946, Utilization of ground-water storage in stream system development: *Am. Soc. Civil Engineers Trans.*, v. III, p. 275-354.

Conover, C. S., 1954, Ground-water conditions in the Rincon and Mesilla Valleys and adjacent areas, Sierra and Dona Ana Counties, New Mexico: *U. S. Geol. Survey Water-Supply Paper* 1230, 200 p.

— 1956, Ground water, its importance to State: *New Mexico Prof. Engineer*, v. 8, no. 7, p. 11-13.

— 1951, Ground-water resources in New Mexico: *New Mexico Prof. Engineer*, v. 3, no. 7, p. 9-12; no. 8, p. 6-9.

— 1961, Ground-water resources—Development and management: *U. S. Geol. Survey Circ.* 442, 7 p.

Conover, C. S., and Akin, P. D., 1942, Progress report on the ground-water supply of northern Lea County, New Mexico: *New Mexico State Engineer 14th and 15th Bienn. Repts.*, p. 283-346 (1953).

Deacon, E. L., Priestley, C. H. B., and Swinbank, W. C., 1958, Evaporation and the water balance, in Climatology, reviews of research: *Unesco, Arid Zone Research X*, p. 9-38.

Harshbarger, J. W., Sept. 1959, Geohydrology of arid lands, Arizona—a case study: *U. S. Geol. Survey open-file rept.*, 28 p.

Kunkel, Fred, 1959, Ground water in the western part of the Mohave Desert region, California, a progress report: *U. S. Geol. Survey open-file rept.*, 41 p.

Lohman, S. W., 1953, High Plains of west-central United States, general aspects, chap. 4 *in* Piper, A. M., and others, subsurface facilities of water management and pattern of supply—type area studies: U.S. Cong., House Comm., Interior and Insular Affairs, *Phys. and Econ. Found. Natl. Resources*, v. 4, p. 70-78.

McGuinness, C. L., 1960, Ground water—a mixed blessing: *XXI Int. Geol. Cong. Part XX, Applied Geology*, p. 7-16, 1 fig.

Meigs, Peveril, 1953, World distribution of the arid and semiarid homoclimates, in Arid zone hydrology reviews of research: *Unesco, Arid Zone programme I*, p. 203-210.

Reeder, H. O., 1957, Ground water in Animas Valley, Hidalgo County, New Mexico: *New Mexico State Engineer Tech. Rept.* 11, 101 p.

Reeder, H. O., and others, 1959, Annual water-level measurements in observation wells, 1951-55, and atlas of maps showing changes in water levels for various periods from beginning of record through 1954, New Mexico: *New Mexico State Engineer Tech. Rept.* 13, 339 p.: Pt. A, High Plains, p. 17-115; pt. B, Pecos River valley, p. 117-219; pt. C, South-Central closed basins, p. 221-251; pt. D, Rio Grande valley, p. 253-269; and pt. E, Southwestern New Mexico, p. 271-339.

Shantz, H. L., 1956, History and problems of arid lands development; the future of arid lands: *Am. Assoc. Adv. Science Pub.* 43, 1956, p. 3-25.

Skibitzke, H. E., and White, N. D., 1959, Physical phenomena in arid-zone hydrology: *U. S. Geol. Survey open-file rept.*, 19 p.

Tannehill, J. R., 1947, Drought, its causes and effects: Princeton, N. J., Princeton Univ. Press, 264 p.

Theis, C. V., 1934, Progress report on the ground-water supply of Lea County, New Mexico: *New Mexico State Engineer 11th Bienn. Rept.*, p. 127-153.

— 1935, the relation between the lowering of the piezometric surface and the rate and duration of pumping of a well using ground-water storage: *Am. Geophys. Union Trans.*, v. 16, pt. 2, p. 519-524.

— 1937, Amount of ground-water recharge in the southern High Plains: *Am. Geophys. Union Trans.*, p. 564-568.

Thomas, H. E., 1955, Water rights in areas of ground-water mining: *U. S. Geol. Survey Circ.* 347, 16 p.

Thompson, D. G., 1929, The Mohave Desert region, California: *U. S. Geol. Survey Water-Supply Paper* 578, 759 p.

Thornthwaite, C. W., 1941, Atlas of climatic types in the U. S., 1900-39: *U. S. Dept. Agriculture, Soil Conserv. Service Misc. Pub.* 421, 7 p., 96 maps.

— 1948, An approach toward a rational classification of climate: *Geog. Rev.*, v. 38, no. 1, p. 55-94.

U. S. Geological Survey, 1960, Natural water resources and problems: *U. S. Senate Select Comm., Natl. Water Resources Comm.*, print 3, 42 p.

White, G. F., editor, 1956, The future of arid lands, papers and recommendations from the International Arid Lands Meeting: *Am. Assoc. Adv. Sci. Pub.* 43.

MAN-MADE CHANGES IN THE WATER RESOURCES OF TRIPOLITANIA, LIBYA

C. VITA-FINZI (1) and R. C. VORHIS (2)

RÉSUMÉ

Au cours des derniers 2.000 ans, l'homme a altéré de façon appréciable l'hydrologie de la Tripolitaine; indirectement en modifiant la végétation et directement (particulièrement au cours de l'occupation romaine et les trois dernières décades) en dérivant et en barrant le eaux de surface et en abaissant les eaux souterraines. Au cours de cette période, la physionomie du drainage superficiel a été modifiée par l'érosion et les dépôts, tandis que les relevés des niveaux des puits modernes indiquent un déclin accusé, dans les régions agricoles du Nord où le pompage par moyens mécaniques est important.

ABSTRACT

For the last 2,000 years man has altered the hydrology of Tripolitania appreciably; indirectly by modifying the vegetation, and directly (particularly during Roman times and the last three decades) by diverting and damming surface waters and drawing on underground resources. During this period the pattern of surface drainage has been modified by erosion and deposition, and modern well records show that there has recently been a sharp decline in the water table of some agricultural areas of the north, where mechanical pumping is heavy.

In most parts of Tripolitania water is scare. Runoff in the wadis is markedly seasonal and the violent floods are short lived; there are no permanent streams although ground water supplies some springs in the limestones of the Gebel. These meagre resources have been used to different degrees of efficiency during the history of settlement, and have suffered some appreciable changes as a result.

1. SURFACE WATERS

From the earliest days of pastoralism fuel collection and agriculture, changes in the natural vegetation have been reflected in altered rates of erosion and deposition, and therefore in density of the drainage net and other aspects of stream geometry(3).

It was not until Phoenician and (even more markedly) Roman times that the surface drainage was modified directly on a large scale by the construction of dams both in stone and in earth across wadis and their tributaries. These accumulated silt and retained flood water, some of which could infiltrate into the banks and the gravels of the wadi bottoms wherever the calcrete binding them was interrupted; silt deposition led to some minor changes in course. Cisterns were dug near every settlement and captured runoff from considerable areas. During this phase the natural vegetation was cleared over large areas, but both the planting of olive and other plants, and careful anti-erosion measures, prevented erosion.

The neglect and overgrazing of the suceeding centuries under nomadic Arab and later Turkish domination allowed erosion to accelerate. Drainage density increased markedly, while water ran to waste.

1) University of Cambridge, England.

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3) Vita-Finzi, C., Post-Roman Erosion and Deposition in the wadis of Tripolitania, A.I.H.S. (Helsinki, 1960), Land Erosion, p. 61-64.

In recent decades, beginning with Italian reclamation and tree-planting, and culminating in dambuilding and terracing by American technicians, the surface waters are being utilized to a fuller extent. A dyke-building tradition has survived in the Berber hill country of the western Gebel and in a few southern wadis but is almost unknown in the east. The largest schemes so far completed include the spreading of flood waters over cultivable areas (e.g., in the Wadi Megenin catchment) and encouraging infiltration into permeable silts. Nevertheless, uncontrolled devegetation, notably of esparto grass in the north and shrubs or trees in the southern wadis, have accentuated the violence of runoff. In many wadis a crop is possible only if floods of the right dimension occur at the right time. Wastage by drainage to the sea and by evaporation is considerable. The solution of the classic problem of eroded watershed and flooded lower reaches is prevented by social complications of which land tenure is the most problematic.

Wells were abundant in Roman, and possibly in Phoenician times, but such wells were limited by their method of construction to tapping only the first water-bearing bed or *prima falda*. The use of buckets and slave and animal labor further served to hold the withdrawals to a quantity which when compared to the total supply was truly only «a drop in the bucket». With the establishment of the colonial farms in Libya by the Italians, the ground-water resources began to be drawn on as they had never been before. Motor-driven pumps along with use of more advanced drilling methods, permitted the second aquifer or *seconda falda* to be exploited heavily. In rather sizeable areas of steppeland turned by the plow or planted to fruits and nuts, the heavy draft on the ground water for irrigation began to represent a form of mining of this most precious mineral asset. The infiltration from the meagre annual rainfall was, and is, far outbalanced by the pumpage. At Castel Benito, 25 km south of Tripoli, the decline of the water table in the *seconda falda* is a rather constant annual figure of about 1 foot or 25 centimetres. Measurements of the water level made when the wells were drilled enable comparisons to be made with water levels as they are now. Declines of the water table are as much as 8 metres in 25 years. In the Suani Ben Adem-Castel Benito area, 21 wells drilled in the years 1936 to 1941 were revisited and measurements made in them of the depth to water. The average decline in these 21 wells was 8.8 metres. No data yet collected can be interpreted to indicate that the rate of water-level decline is decreasing. Rather, the data indicate that the water levels are going down, down, down with about the same amount of dewatering of the aquifer each successive year.

ÉTUDE DÉTAILLÉE (ALIMENTATION)

DETAILED STUDY (RECHARGE)

GAMMA-METHOD FOR OBSERVING OF DYNAMICS OF MOISTURE PERCOLATING IN SOILS AND CONSIDERED IN EVALUATING OF GROUND WATER RESOURCES

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All-Union Scientific Research of
Hydrogeology and Engineering Geology, U.S.S.R.

ABSTRACT

The consideration of moisture, entering as a result of percolation, is of particular importance for evaluating of ground water resources.

For observing of moisture dynamics in soils of the zone of aeration special balance test-sites are installed. Studying of moisture dynamics is connected with repeated drilling for systematic soil sampling. Repeated drilling of a small area leads to disturbance of the natural structure and texture of soils. In addition, this procedure is labour-consuming.

The gamma-method for observing of the dynamics of moisture percolating soils is now being put into practice by the All-Union Scientific Research Institute of Hydrogeology and Engineering Geology, U.S.S.R.

This method is based upon gamma-ray absorption by soils. It is considered that the dry density of the soil down the zone of heaving is unchangeable and the degree of gamma attenuation changes as a result of change in moisture content.

The observation equipment permits to conduct measurements up to a depth of 20 m. The battery portable field scaled radiometer is used as a measuring device.

The data obtained in the field show that the error of measurement by this method does not exceed 1.5-2.0 % and labour consumption reduces to 3-5 times.

In evaluating ground water resources essential importance has the considering of moisture percolating in result of leakage. In the practice of hydrogeological investigations on the moisture dynamics in the aeration zone are arranged special balance test-sites. The study of moisture dynamics are connected with repeated drilling for systematic soil sampling. Repeated drilling of a small area leads to disturbance of the natural structure and texture of the soil in places where measurements are taken. Besides, such procedures are very labour consuming.

At present, into the practice of hydrogeological investigations is inculcated by the authors the gamma-method of observations on dynamics of moisture percolating into soils. This method is a more progressive one.

The method of determinating moisture during hydroregimen investigations is based upon the law of the attenuated intensity of the gamma-ray flow by a layer of most soil.

$$N = N_0 \bar{e}^{\mu w \varrho w l} \qquad (1)$$

Here and further:

N_0 — is the gamma-ray flow intensity without an absorber,
N — the gamma-ray flow intensity after passing through the soil layer,
e — base of the natural logarithm,
l — thikness of the soil layer examined by radioscopy,
μ_w, μ_1, μ_2— mass absorption coefficients for the gamma radiation in moist soil, in the soil skeleton and in water,
ϱ_w, ϱ_c — volumetrical weight of moist soil and of the soil skeleton,
W — weigt moisture.

Taking into account the known proportions:

$$\varrho_w = \varrho_c \, (1 + w) \tag{2}$$

and

$$\mu_w = \frac{\mu_2 + w\mu_1}{1 + w} \tag{3}$$

and supposing also for the constant points of observations:

$$\varrho_c = \text{Const.} \tag{4}$$

we obtain:

$$w = A \, ln \frac{N_0}{N_i} - B \tag{5}$$

where

$$B = \frac{\mu_1}{\mu_2} \tag{6}$$

Conformable calculations and measurements have shown that coefficient B for the given irradiation source and for the most wide-spread sand-clayey soils is of constant value (for cobalt — 60 $B = 0.9$).

Exceptions are soils, containing considerable additions of heavy elements, for instance, iron.

Value of coefficient A is determined by limit conditions at the moment the observations point is arranged, according to thermostatic weight and radiometric measurements:

$$A = \frac{w^1 + B}{ln \dfrac{N_0^1}{N_i^1}} \tag{7}$$

where

w^1, N_0^1 and N_i^1 are conformably the natural moisture in the points being measured, determined by the weight method, the initial and final intensity of gamma-radiation on the day when the observation point is arranged.

Value of coefficient A is determined separately for each observation horizon on moisture dynamics. If the value of constant coefficients A and B is known, and after the measuring upon each horizon the attenuation degree of gamma-radiation (No/Ni), it is possible to obtain, according to formula (5) for each following measurement day, the value of weight moisture. It is practically convenient to elaborate once, according to the first day of datum mark measurements, calibrating graphs, which in future will considerably facilitate the technique of moisture determination (fig. 1).

In applying calculation formulae, taken into account is the difference between mass absorption coefficients for water and soil skeleton, which is for average (medium) energies (cobalt — 60) about 10%.

An essential influence upon the precision of moisture determination under field conditions is exerted by taking into account the registered disseminated gamma-radiation. In field instruments, applied by the authors, the registration of gamma-radiation is carried on under geometry conditions of a wide pencil. Application of

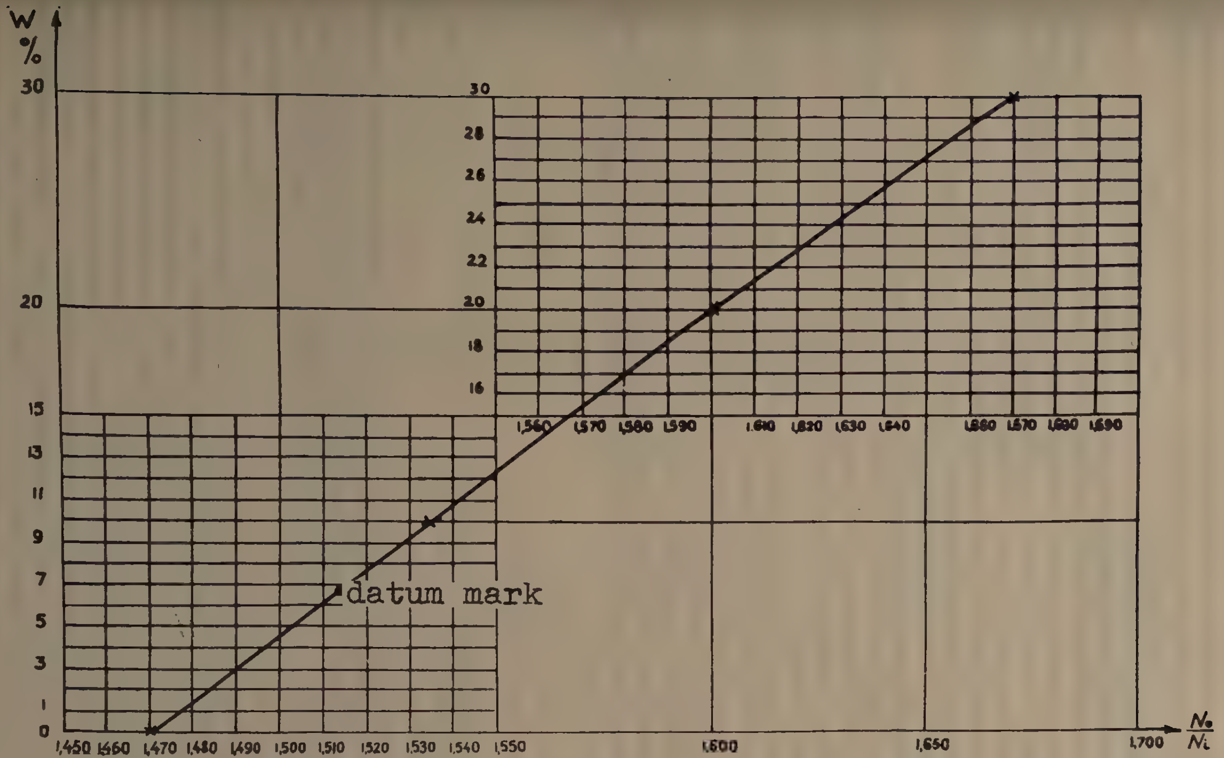

Fig. 1. — Calibrating graph of moisture determination by the gamma-method in the aeration zone.

halogene gamma-counters of the CTC-6 type, having an obstruction of the spectral characteristics in the region of small energies, allows to lower the indication of disseminated gamma-radiation. Besides, determination of coefficient A from limit conditions for each measurement horizon allows also to take into account the influence of disseminated gamma-radiation and to lower to a minimum the error on account of this factor.

Constancy of coefficient B for the given gamma-radiation source and for most wide-spread sand-clayey soils is confirmed experimentally.

In the methods'positions of principle is made an assumption on the constancy of volumetric weight of the soil's skeleton for the entire period of regimen observations on moisture. It must be noted, that this assumption is sufficiently correct for sandy soils. For clayey soils, it is done only lower than the zone of heaving.

In relation to this, it is recommended according to the proposed methods to carry on observations on moisture dynamics for sandy soils from a depth of 0.2 m and for heaving soils — from the depth of freezing.

Maximum depth of the method's application is limited by the practical possibility of boring two bore holes at a distance — 0.5 m to the depth of their rapprochement or of their withdrawal to more than the value of one diameter of the bore hole. Usually this requirement is feasible down to a 10-20 m depth and under careful execution of boring.

As we know, there exists the soil free moisture or moisture bound in some way. Along with this, moisture is present in diverse aggregate state. The relative moisture content in this or another agregate state is subject to modifications.

The methods of moisture definition, based upon the absorption of gamma-radiation, is sensitive to modifications in the moisture content during regimen observations independently from the aggregate state and connection forms into which moisture enters. The gamma method notes each moisture increase, including moisture being in a state of vapour.

EQUIPMENT AND APPARATUS

For the execution of observations on moisture dynamics in the aeration zone following equipment and apparatus are used;

Two parallel bore holes are bored at a 0.5 m distance from one another and they have 3 inches tubing. For the measurement of the initial gamma-radiation intensity without an absorber are left over the surface of the site ends of the tubing 0.3 m high. In equipping observation points on arable land the protruding ends of the tubing were made removable so as not to prevent sultivation of the field. Upon the ends of the tubing are rut caps (3) (fig. 2) with tape-measures (1) having steel measuring tapes (5) of needed length fixed upon them. At the end of one of the measuring tapes is fixed a holder (9) having a preparation of cobalt-60 (11) with an activity of 2 mg equ. radium. The caps on the tubing are fixed by stopper-screws (4).

The other tape has on the map-hook (7) a case with a battery considering of three gamma-counters of the CTC-6 type. The gamma counters are connected by a cable (6) with the field impulse radiometer (12). For the execution of measurements the gamma preparation and the calculation tubes are placed at the needed depth, the measurement tape being fixed by a stopper screw (2).

Transportation of the gamma-preparation to the place of measurement is done in a protective lead container (16).

The described equipment is easily portable and is used to serve serveal observation points.

The sequence in executing measurements and the treatment technique of experi-

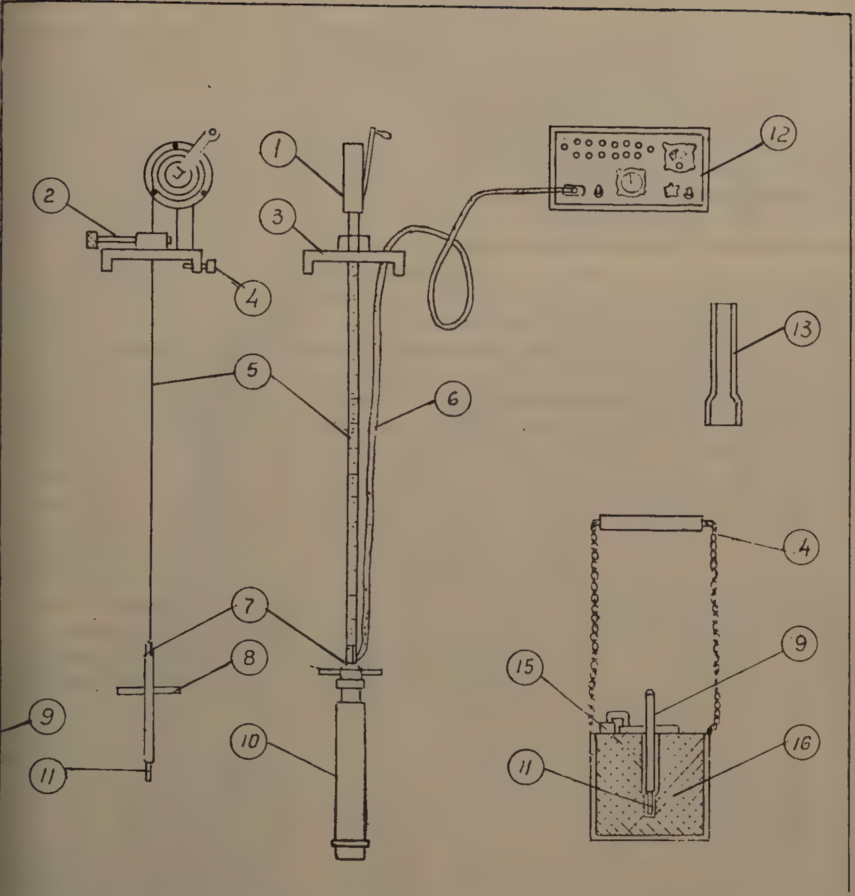

Fig. 2 — Equipment and apparatus for the gamma-method in moisture determination: 1. Tape-lines; 2 — stopper screw of tape; 3 — caps; 4 — stopper screw of cap; 5 — measuring steel-tapes; 6 — cable; 7 — snap hooks; 8 — limiting washers; 9 — holder; 10 — counters'case; 11 — gamma-preparation; 12 — radiometer; 13 — sochet pipe; 14 — container handle; 15 — container lock; 16 — lead protection.

mental data are not elaborate. In the process of boring bore-holes at depths outlined for observations are taken soil samples for moisture determination by the drying method. During the same day, after tubing the bore holes, are carried on radiometrical measurements at the same horizons. Further according to formulae (5) and (7) is traced a calibrating graph for each horizon (fig. 1). All further work on observing moisture migration is reduced to the execution of radiometrical measurements in the outlined horizons and to determinate, according to corresponding graphs, the sought for moisture.

The examined methods and apparatus were tested in a sufficiently vast manner under various climatic and hydrogeological conditions.

As an example, let us examine data on moisture dynamics observations in the aeration zone, which are carried on at present in one of the Central Asia Republics

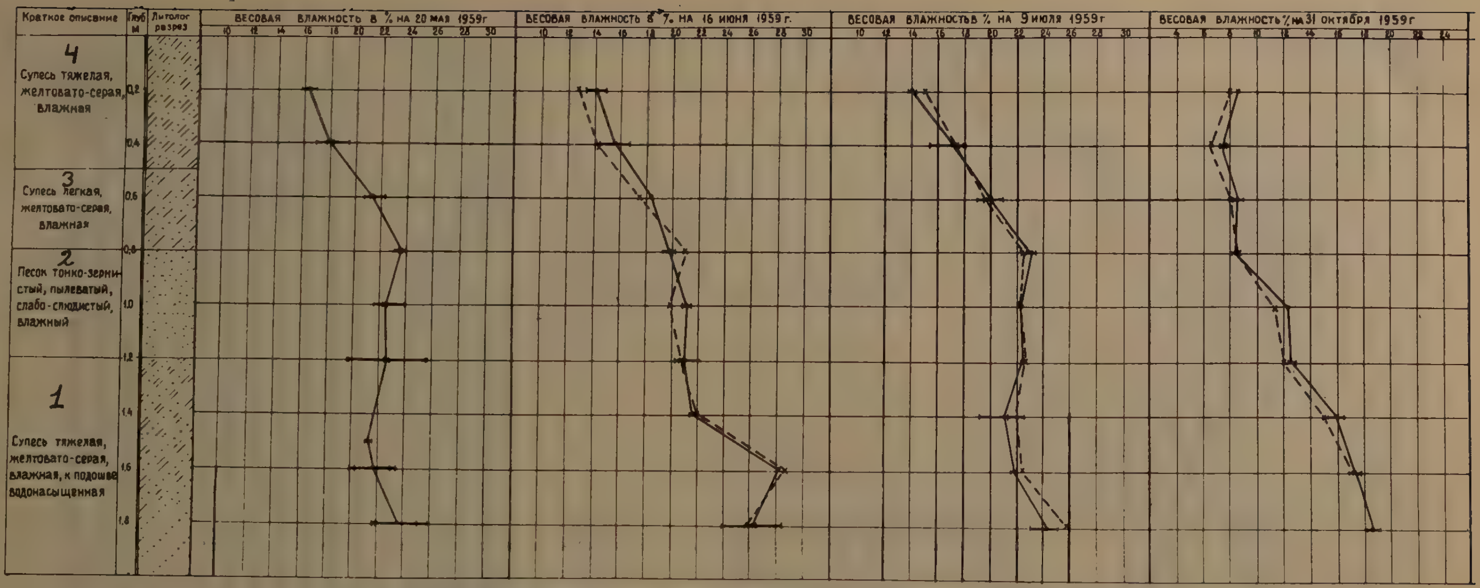

Fig. 3. Results of moisture dynamics observations for the aeration zone in the delta of the river Murgab.

——— moisture according to data obtained in drying the samples;
– – – – – moisture according to data obtained by the gamma-method.
1 — Heavy yellowish-gray moist sandy loam, saturated at the base;
2 — Very fine dust-like slightly micaceous moist sand;
3 — Light yellowish-gray moist sandy loam;
4 — Heavy yellowish-gray moist sandy loam;
5 — Brief descriotion;
6 — Depth (m);
7 — Lithological section;
8 — Weight moisture (%); May 20,1959;
9 — Weight moisture (%), June 16,1959;
10 — Weight moisture (%), July 9,1959;

of the Soviet Union. Measurements were effectuated under conditions of heavily saline, loamy and sandy soils. In order to verify the reliability of radiometric measurements parallelwise were done boring with soil sampling and moisture analyzing by the drying method. Observation results on moisture modification during 4 months are represented in fig. 3. The first graph shows the moisture modification curve with depth, traced on the first day when the observation point was organized, according to data of drying the obtained soil samples. On each other graph are traced two curves, on which the results of radiometrical measurements are traced by dots. As it may be seen from comparing data on moisture determination between the gamma-method and the drying method, the obtained precision is quite satisfactory and attains no more than 1-1.5 % of weight moisture.

Along with this, it is necessary to note, that during the process of boring, soil sampling was done with three and four repetitions. Analyzing the results of moisture determination by the drying method, it was always found that the samples taken from one and the same depth differ in moisture by 2-3 and sometimes even by 5%. Hence, it is clear that in certain parts of the soil massif the precision of the drying method is very conventional. In relation to this the gamma-method gives for the examined problem more objective data on soil moisture. The soil volume, being exposed to analyzing is in this case no less than 3000-4000 m^3 and an accidental character of it is less likely. Taking into accounts this circumstance, it may be thought that mistakes in moisture determination by the gamma method, due only to errors of radiometrical measurements, attain no more than 0.5-1.0 % of absolute moisture.

At present a series of hydrogeological organizations in the Soviet Union, that carry on systematic investigation of moisture dynamics in the aeration zone, in order to take them into account during evaluation of ground water resources, widely apply the gamma-method, as it is a more progressive and economically more advantageous method for effectuating hydrogeological investigations.

Royaume du Maroc
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NAPPES DE BERRECHID ET DU CHARF EL AKAB MÉCANISME D'ALIMENTATION ET ÉVALUATION DES RESSOURCES EN EAUX SOUTERRAINES. RECHARGE ARTIFICIELLE

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Résumé

Recherches des méthodes permettant la simplification des problèmes posés et détermination du mécanisme d'alimentation; calcul des caractéristiques facilitant l'évaluation, dans les deux cas, des ressources en eaux souterraines.

Application de la recharge artificielle pour le Charf el Akab.

Summary

An investigation of methods to simplify arising problems and determination of feeding mechanism; a computation of the characteristics which make it casier, in either case, to assess underground water ressources.

Application of the artificial refilling technique to the Charf el Akab.

Nous passerons en revue, sans trop nous attarder, l'étude du mécanisme d'alimentation des nappes aquifères, appliquée à deux régions au Maroc. En effet, l'étude détaillée du mécanisme d'alimentation pour chacune de ces régions conduirait à un rapport trop long; or, d'une part, l'état actuel d'avancement des sciences hydrogéologiques permettant l'application de méthodes nouvelles à la compréhension et résolution de tels problèmes, d'autre part, la brièveté avec laquelle il faut rédiger ces notes nous poussent à esquisser le sujet en en donnant simplement l'esprit, les caractères généraux et les résultats.

Nous nous attacherons donc à donner des exemples plutôt que de faire des études approfondies, lesquelles d'ailleurs peuvent être mises à la disposition des spécialistes étrangers qui s'y intéresseraient.

Deux nappes dont l'étude est particulièrement simplifiée, par une disposition géologique naturelle favorable seront passées en revue.

— La nappe de Berrechid.

— La nappe du Charf El Akab (Tanger)

Si la première a déjà fait l'objet d'un rapport à Helsinki au congrès de l'A.I.H.S. (Association Internationale Hydrologique Scientifique en 1960) et qui mérite qu'on y revienne un peu, l'étude de la seconde est inédite et originale et doit faire incesssamment l'objet d'une communication fort éfoffée.

1. Nappe de Berrechid (rapport MM. Moullard, R. Hazan)

L'étude du mécanisme de l'alimentation de cette nappe a été précédée par *une étude géologique détaillée* :

En effet, nous avions pensé que la connaissance géologique de *s* terrains limitant la nappe ou la contenant, pourrait nous guider efficacement dans le méthode à utiliser pour arriver rapidement à comprendre le mécanisme d'alimentation et l'évaluation des ressources aquifères.

Effectivement, l'ensemble de Berrechid se présente en surface comme une fosse de subsidence, limitée au Sud par les calcaires marneux du Crétacé, et ailleurs par des formations primaires : schistes et quartzites. Les terrains de remplissage sont formés de grès marins et dunaires du Pliocène.

Le bassin est endoréique et n'a aucun exutoire vers la mer.

L'étude géographique et géologique, a montré que l'alimentation de ce bassin ne peut se faire que par les eaux de pluie et par infiltration des eaux des cours d'eau arrivant du Sud et disparaissant sous la plaine. Ainsi donc, l'alimentation de cette plaine est limitée à deux paramètres du fait de son endoreïsme, et de sa prédisposition géologique en cuvette.

1.1. *Apport par les eaux de pluie* :

L'ensemble aquifère de la nappe est recouvert d'alluvions quaternaires constitués de limons généralement très peu perméables; témoins les plans d'eau qui se constituent en hiver aux environs de Berrechid. D'autre part, la pluviométrie 368 mm est faible par elle-même.

La surveillance des puits témoins a montré plusieurs zones (Nord, Ouest) où la nappe a un niveau presque statique : la pluie ne l'atteint pas et ne l'influence guère.

C'est ainsi que l'on a pu estimer que la fraction d'eau arrivant à la nappe et consécutive aux pluies est certainement *très faible.*

1.2. *Apport par infiltration naturelle des cours d'eau au Sud de la plaine* :

L'observation des puits témoins disposés rationnellement du Sud au Nord, montre qu'il y a une relation évidente entre les fluctuations des niveaux d'eau des piézomètres les plus en amont, et le régime d'écoulement des eaux d'oueds du plateau dominant la plaine. C'est ainsi que l'on enregistre dans les nappes des remontées du plan d'eau dès le mois de Septembre : „la remontée débute dans le courant du premier mois de pluie"; elle dure tout le long de la période humide.

Ayant ainsi établi la cause principale de l'alimentation de cet ensemble aquifère, il reste à évaluer les ressources en eaux souterraines.

Celles-ci ont été calculées de deux manières :

— Apport des oueds en année moyenne.

— Réaction de la nappe sous cet effet d'alimentation.

L'apport par les oueds a été calculé, connaissant les conditions de pluviosité et d'écoulement : pluie, périodes, bassin versant, coefficient de ruissellement. Le volume d'eau apporté à la nappe a été ainsi estimé à 65,5 Mm^3.

La réaction de la nappe, pour cet apport d'eau a été suivie sur les multiples puits piézomètres (100) situés dans l'ensemble aquifère.

Il a ainsi pu être dressé des cartes annuelles de courbes d'égale remontée maximum du niveau d'eau. La planimétrie des zones comprises entre ces courbes a permis le calcul *des volumes de terrains occupés* par la pénétration des eaux.

Plusieurs sondages (30) ont été en outre effectués sur lesquels de multiples essais de débit ont été exécutés en vue de calculer les *caractéristiques hydrogéologiques* des différents terrains aquifères tels que coefficient d'emmagasinement, transmissivités, etc.

C'est ainsi que l'on a pu calculer, zone par zone, les quantités d'eau ayant pénétrées cette année dans la nappe de Berrechid, et constituant l'apport annuel différent de ce que l'on peut appeler les „réserves proprements dites". Le volume total d'eau ainsi calculé est pour cette année. moyenne, de 67,6 Mm^3.

Les deux évaluations sont proches, compte tenu de l'étendu du terrain et des hypothèses faites pour les calculs.

Il semble donc qu'un volume de 65 Mm^3 puisse être utilisé annuellement et en moyenne.

2. NAPPE DE TANGER

La nappe dite du Charf el Akab est utilisée pour l'alimentation en eau de la ville de Tanger.

L'étude géologique détaillée a montré que cette nappe est une sorte de baignoire constituée de terrains aquifères, de grès et sables du Pliocène affleurant par endroit et reposant sur les marnes du Miocène lesquelles affleurent aussi largement, sur les bordures.

C'est un bassin fermé qui ne reçoit d'alimentation que par *les eaux de pluie* ; aucun cours d'eau ne le parcourt; aucune alimentation occulte non plus.

Ce bassin de 20 km² est exploité par une dizaine de stations de pompage refoulant leurs eaux vers la ville de Tanger au rythme de 9 à 12.000 m³/j ; soit 100 à 150 l/s.

Plusieurs piézomètres ont été exécutés en vue de suivre l'évolution en cours de pompage (voir carte nº 1).

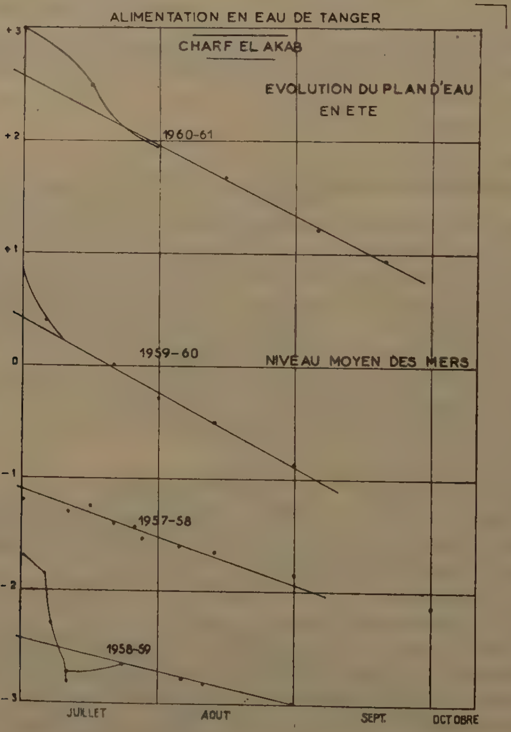

Fig. 1

L'exploitation étant ce qu'elle est pour Tanger, il était indispensable de serrer de près le mécanisme d'alimentation de cette nappe pour en calculer ou évaluer le débit d'apport. Mais cette opération ne fut entreprise que lorsque l'on s'aperçut que l'exploitation de cette nappe se faisait à un taux supérieur à son alimentation naturelle, puisque le niveau moyen de la nappe ne cessait de décroître et s'approcher du 0 moyen des mers. C'est la raison pour laquelle des études poussées et urgentes de Messieurs AMBROGGI R., et HAZAN R. ont été entreprises.

Nous avons déjà dit qu'elle était la source, unique, d'alimentation de cette nappe. l fallait alors l'évaluer pour se faire une idée du déficit d'exploitation.

L'observation conjointe des niveaux piézométriques de la nappe établie sur lusieurs années et du régime de la pluie a permis de prouver que la nappe n'était uère influencée extérieurement pendant les mois de Juillet, Août, Septembre. (N° 2).

Durant cette même période (3° trimestre) nous avons pu évaluer la baisse générale e la nappe en fonction de l'exploitation. C'est ainsi que l'on a une baisse de :

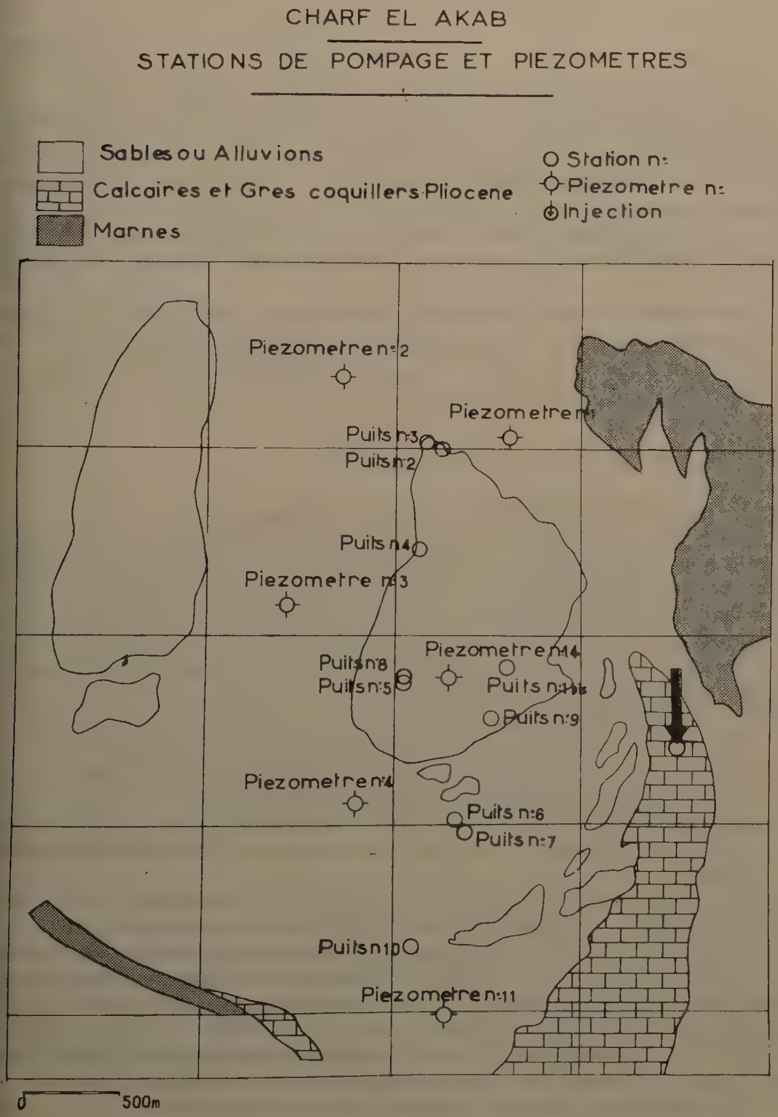

Fig. 2

Année	Baisse par mois m	Volume pompé par mois m³	Rabattement pour I M m³ m
1957 - 58	0,45	300.000	1,50
1958 - 59	0,30	210.000	1,50
1959 - 60	0,60	360.000	1,65
1960 - 61	0,55	330.000	1,70

Ainsi donc on peut prendre en moyenne un rabattement de 1,60 m, sur un piézomètre éloigné de la zone d'influence transitoire des stations, pour un prélèvement à la nappe de I Mm³.

Cette détermination graphique va nous permettre de déduire toutes les caractéristiques propres au Charf et prévoir le comportement de la nappe sous toutes les influences diverses.

La connaissance de la donnée ci-dessus permet entre autre le calcul du coefficient d'emmagasinement moyen de la nappe. (Du moins entre les niveaux -4 et $+16$).

$$\text{Soit : } S = \frac{10^6}{20\ 10^6 \times 1{,}60} = 3{,}1.10^{-2}$$

ce qui constitute une valeur normale pour les grès.

2.1. *Évaluation de l'apport annuel météorique à la nappe* :

Cet apport est évidemment variable selon l'année et la quantité de pluie tombée.

L'observation des fluctautions du niveau d'eau pendant une année, en fonction de la caractéristique calculée ci-dessus permet le calcul de l'apport dû aux précipitations et infiltrations des eaux de pluie.

C'est ainsi qu'en année normale, où il n'y a eu que pompage dans la nappe, on a pu calculer les relations suivantes (R. Hazan) pour l'année 1956-1957.

— Pour h = 640 mm de pluie

— Le volume d'eau nouveau correspondant est de 1,87 Mm³.

Il y a donc eu en 1956-1957 un apport annuel de 1,87 Mm³ consécutif à l'infiltration des eaux de pluie dans les grès et sables du Pliocène.

Cet apport constituant approximativement la moitié de la consommation annuelle en eau de la ville de Tanger, il n'était pas étonnant de voir s'abaisser le niveau général de la nappe.

Ces considérations nous ont permis d'élaborer un avant projet pour subvenir aux déficits annuels qui se cumulaient ainsi d'année en année.

C'est ainsi qu'est née l'idée de faire subir à cette nappe ,,une recharge artificielle''.

Des dispositions naturelles favorables, affleurement des grès très fissurés, terrains de bonne perméabilité, la présence d'un cours d'eau saisonnier à 8 km au Sud du Charf ont permis la réalisation de ce projet *de recharge artificielle*.

Celle-ci est actuellement en cours d'exécution depuis Juin 1958; elle constitue la première tentative au Maroc et en Afrique de ce mode élégant de palliatif.

C'est ainsi qu'un volume de 1 Mm³ est injecté annuellement en cinq ou six mois environ durant la période humide.

Les prévisions fondées avant l'exécution des travaux, se vérifient régulièrement et la nappe ainsi rechargée artificiellement recouvre peu à peu (1 à 2 m tous les ans) sa situation d'antan.

ON THE MECHANISM OF THE REPLENISHMENT OF AQUIFERS IN THE NEGEV (THE ARID REGION OF ISRAEL).

A progress report

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ABSTRACT

The normal pattern of run-off in arid regions with other than highly permeable soil is conditioned by the scarcity of precipitation. Soil moisture above air dryness occurs only in the few top decimettes and only after precipitation. Below this narrow belt, by gravity and accretion of underground water directly through precipitation does not occur — except at places where water happens to accumulate on the surface and downward movement is thus temporarily possible.

When non-sandy top soil has reached field capacity, overland flow starts, forms flood run-off in wadis and accumulates temporarily in depressions. Floods and temporary accumulations in depressions may become influent under favourable hydrogeological conditions. The same may occur un case non-ephemeral water courses cross arid regions.

Replenishment through flood water is generally fresh; that caused by temporary accumulation in depressions may be brackish or saline.

These are the only cases in which replenishment of underground water occurs in arid regions with other than highly permeable soil. Techniques of analysing the underground water flow should be adapted to these special conditions prevailing in arid regions.

RÉSUMÉ

Le comportement normal de l'écoulement superficiel dans les régions arides n'ayant pas de sous-sol hautement perméable est conditionné par la rareté des précipitations. L'humidité du sol n'existe que dans les quelques décimètres supérieurs et seulement aprés les pluies. En-dessous de cette faible épaisseur, le sol est continuellement sec. Il en résulte que le mouvement descendant de l'eau par gravité et l'alimentation d'une nappe aquifère directement par les précipitations ne se produisent pas — à l'exception d'endroits où l'eau parvient à s'accumuler à la surface rendant un mouvement descendant temporairement possible. Quand le sol supérieur non sablonneux a atteint sa capacité de saturation, l'écoulement de surface commence, provoque un écoulement dans les ,,Wadis'' et s'accumule temporairement dans les dépressions. Crues et accumulations temporaires dans les dépressions peuvent exercer une influence dans le cas de conditions hydrogéologiques favorables. Le même cas peut se produire si des envois d'eau non-éphémères traversent des régions arides.

La recharge par l'eau de crue est en général non saline; celle par l'accumulation temporaire dans les dépressions peut être saumâtre ou saline. Ce sont là les seuls cas où la recharge des eaux souterraines se produit dans les régions arides qui n'ont pas de sols hautement perméables. Les techniques d'analyse des courants souterrains doivent être adaptées à ces conditions spéciales propres aux régions arides.

The replenishment R_u of aquifers in the non-arid region of the eastern Mediterranean basin can be depicted by the equation

$R_u = \alpha (P - P_0)$ Units: mm p.a. (2),(3) (*)

$\alpha < 1$ a dimensionless coefficient, characteristic of the catchment which replenishes the aquifer

P (mm p.a.) the annual precipitation over the catchment

P_0 (mm p.a.) a threshold value, characteristic of the catchment.

(*) Numbers in brackets refer to the bibliography at the end of this paper.

The replenishment results from rain water which infiltrates into the soil in excess to its field capacity and continues its downward percolation to the nearest phreatic aquifer. In addition, influent ephemeral and non-ephemeral water currents may contribute to the replenishment.

In the Judean hills and the Coastal Plain situated to the west the threshold value P_0 of the equation is 360 mm p.a. (2)

Ecological investigations have shown that the long term mean precipitation of 350 mm p. a. is the lower limit for the continuous cover by the natural vegetation of the local maquis (6). Below this limit, only patchy vegetation is found on non-sandy soils. It becomes sparser with decreasing rainfall. It thus appears that in the region under references areas with an annual rainfall of less than 350 to 360 mm should be considered as arid. In these areas the soil moisture derived from the rain is entirely consumed by mostly patchy vegetation and by the evaporation from the soil, exepct in the wadi beds and in sandy soil and dunes. The non-sandy soils outside the wadi beds are wetted above air dryness to a shallow depth only. This depth decreases with the rainfall. Below the wetted zone, the soil moisture is expected to show a sharp drop to almost permanent air dryness. Such a zone of permanently dry soil indicates that no replenishment of underground water by downward percolation occurs, except perhaps during very heavy rains over areas with shallow underground water, covered by a highly permeable soil. Such heavy rains are very infrequent. In the beds of water courses — ephemeral as well as non-ephemeral — the flow of water, whenever it occurs, wets the soil to a considerable depth, saturates it and causes downward percolation to the next phreatic aquifer if the flow lasts sufficiently long.

Investigations carried out by D. Hillel and N. Tadmor (4) in the arid central highlands of the Negev (annual rainfall between 50 and 100 mm) proved that in the area investigated rain penetrated on hilltops only some 20 cm on the average, on rocky slopes — some 60 cm, in sandy plains some 85 cm and in loess plains some 15 to 30 cm. Below the wetted belt the soil moisture remains almost permanently below wilting range. In wadi beds — both gravel and loses — moisture had penetrated after each flood to the maximum depht of sampling, viz 5m. Therefore, underground water replenishment in the investigated area occurs only through water flowing in the wadi beds.

Overland flow in the Negev starts rather shortly after a few mm of rain per hour have fallen and its rate is pretty high. The reason may be found in the fact that the rain seals the surface of non-sandy soils in this region. Run-off measurements carried out in small catchments in the Negev covering 0.3 and 0.9 km^2 respectively corroborate this fact. The four years' average storm water run-off observed was 16 and 8 mm p.a. The rainfall over the catchment, averaged for the same period, was 96 mm p.a.(*) The average run-off from a 40 km^2 catchment into which the two small catchments quoted above discharge was 3mm p.a. only.(**) One may fairly assume tath the very high storm water run-off observed in the short natural drainage channels of the small catchments indicates the high overland flow in the catchments whereas that observed in the main wadi draining the 40 km^2 has already markedly been reduced by downward percolation which eventually would replenish the local underground water horizon. The average storm water run-off observed in major wadis draining the Negev is still lower.

A research into the methods of cultivating Nabatean and Byzantine farms in the Negev is now in progress. It has supplied some information relating to the overland flow in the region (1), (5). The farms which had been abandoned during the conquest of the country by the Arabs (636 A.D.) are situated in a belt with an average rainfall

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(*) By courtesy of the Director, Hydrological Service.
(**) Bij courtesy of the Director, Soil Conservation Service.

of some 100 mm p.a. They are still in a relatively good state of conservation. Cultivation was based on spate irrigation. In many cases, the farmed area used to be irrigated by the overland flow from slopes above the farm and conveyed thither by means of an elaborate system of interceptors and conveyers with regulators. The ratio catchment: irrigated farm land has been computed for 100 such farms. It varies from 17: 1 to 30: 1 with an average of 20: 1. (5) The whole system is now in ruins and the overland flow drains uncontrolled into the wadis.

A few farms, their catchments, channels and regulators have recently been resuscitated and operated as part of the research programme. They have yielded one reasonable crop per year with irrigation at the total rate of some 400 mm per crop, obtained from the canalized overland flow. (***)

As the long term average precipitation over the area does not appear to have much changed since the farms have been operated, one may assume that the ancient farmers based their agriculture on an average overland flow of approximately 400: 17 to 400: 30 or 24 to 13 mm p.a. These values exceed considerably the storm water run-off in the major wadis draining the area under review.

The overland flow is in most cases fresh — unless the soil over which it flows is saline. The same holds good for the storm water run-off in the wadis. The water percolating through the wadi beds into the underground water has initially the same salinity as the flood water. It can pick up salinity on its way to the aquifer which it replenishes in case it percolates through saline strata. Non-ephemeral currents flowing through arid regions will certainly effect the hydrological cycle in the same way as the storm water run-off in wadis.

Water accumulating in depressions becomes more saline through evaporation. Underground water replenished from such stagnant accumulations of water must be expected to be the more saline, the longer the accumulated water has been exposed to evaporation.

It may be concluded from the foregoing that underground water which occurs in regions with an annual rainfall of 100 mm and less is replenished only by water flowing in the natural drainage channels or by water accumulated in depressions. The flow of water may originate from storm water run-off and/or from non-ephemeral currents. The replenishment by these surface water sources rises with the permeability of the wadi beds. Replenishment by precipitation percolating into the aquifer does not occur — except perhaps through very porous soil and, very occasionally, after exceptionally heavy and extended rainfalls.

The ecology and the hydrology of the area under review indicate that flowing and stagnant surface water are the only or, at least, the predominant source of replenishment, as long as the annual precipitation does not exceed 350 to 360 mm and the soil is not highly permeable (e.g. sand, gravel, fissured rock).

The replenishment from the flow in wadis can be estimated as follows:

1) Storm water run-off.

The run-off from small catchments measured in channels with a low permeability can serve as a significant indication of the overland flow whereas the run-off measured in the main wadis represents the remnant flow which does not infiltrate and replenish the aquifer. (Units: mm) The difference can serve as a first estimation of the replenishment, as the area in the wadi bed where water evaporates and is transpired by the vegetation is a negligible fraction of the catchment and as temperatures during floods are generally low and air humidity high. The accuracy of such an estimation is greatest in the case of highly permeable beds of the main wadis with a low field capacity, and vice-versa.

2) Non-ephemeral base flow.

(***) Information supplied by the courtesy of Prof. M. Evenari.

The difference of flow between two discharge sites represents the replenishment plus evapotranspirations in the wadi bed. The latter will be a high percentage of the flow if the flow is low, temperatures are high and air humidity is low. In such cases, the inacuracy of estimating the losses through evapotranspiration may prevent the application of this method.

The contents of the present paper may apply also to other arid regions with similar climatic and soil conditions.

BIBLIOGRAPHY

(1) M. Evenari, 1961, The use of water for the development of desert agriculture in the Negev. Paper presented at the 4th Congress of Scientific Societies, 1961, Rehovot. *Bulletin of the Research Council of Israel.* Jerusalem, Israel.

(2) M. Goldschmidt and M. Jacobs, 1958, Precipitation over and replenishment of the Yarqon and Nahal Hatteninim underground catchments. *Hydrological Service.* Jerusalem, Israel.

(3) M. Goldschmidt, 1959, On the water balances of several mountain underground water catchments and their flow pattern. *Hydrological Service.* Jerusalem, Israel.

(4) D. Hillel and N. Tadmor, 1960, Water regime and vegetation of plant habitats in the central Negev. (Stylographed) National and University Institute of Agriculture. Rehovot, Israel.

(5) N. H. Tadmor, L. Shanan and M. Evenari, 1960, The ancient agriculture in the southern Negev, VI. National and University Institute of Agriculture. Rehovot, Israel.

(6) M. Zohary, 1955, Geobotany (published in Hebrew). Sifriat Hapoalim. Merhavia, Israel.

Royaume du Maroc
OFFICE NATIONAL DES IRRIGATIONS

MPORTANCE DE L'ALIMENTATION LATÉRALE DES NAPPES PHRÉATIQUES EN ZONE ARIDE

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ÉSUMÉ

Le calcul des surplus du bilan hydrique, en zone aride ou même semi aride, et en évidence l'impossibilité ou tout au moins l'irrégularité interannuelle des filtrations des eaux de pluies tombées sur les plaines limoneuses.

Ainsi la permanence d'une réserve souterraine phréatique ne saurait être assurée ans l'apport allogène de nappes formées en zone plus humide et sur des aires où la thologie permet une infiltration rapide (calcaires, conglomérats...).

Quelques exemples marocains de ce phénomène de relai hydraulique, classique ais particulièrement vital en zone aride, sont décrits rapidement.

UMMARY

«Importance of lateral recharge for phretic water-tables in arid zone»

From computing the water-balance surplus in arid and semi arid zone, the mpossibility or at least interannuel irregularity of slimy plains rainwater infiltrations eams obvious.

So a permanent phreatic under ground reserve would be impossible, whitout its echarge from water tables formed in more humid zones and in areas where lithology llows a rapid infiltration.

Some Moroccan examples of this classical hydrogeological phenomenon of ydraulical relieving, of hightest importance in arid zone, are briefly described.

Les précipitations sont, dans la quasi totalité des cas, à l'origine des nappes quifères des grandes plaines, de façon directe ou indirecte.

Mais en zone aride ou semi aride, l'infiltration à la verticale des pluies tombées ur les plaines limoneuses elles-mêmes est nulle ou irrégulière. En effet ces zones ont définies par THORNTHWAITE (1) comme celles où l'indice d'humidité est nul — u tout au moins inférieur à 10. Sous de tels climats, il est bien évident que les pluies itôt tombées sont évaporées, dans leur totalité, par suite de la ciccité de l'air; ou, lus exactement, le bilan hydrique moyen ne fait apparaître que rarement un surplus otal supérieur à 100 mm (quantité arbitrairement proposée par THORNTWAITE pour les plaines limoneuses comme eau de rétention, retournant à l'atmosphère par la suite. l est bien évident que pour des plaines constituées d'alluvions grossières, cette quanité serait moindre.

Certes les calculs de THORNTHWAITE — qui est un climatologue — sont menés ur des moyennes; or si l'on peut considérer que l'évapotranspiration potentielle nnuelle (Ep)(*) est un élément relativement constant d'une année à l'autre, il faut ar contre se rappeler que la variabilité élevée des précipitations (P) caractérise la one aride tout autant que le manque d'eau. Aussi le calcul de la hauteur d'eau oustraite à l'évaporation (surplus du bilan hydrique qui ruisselle ou qui s'infiltre)

(*) Abréviations employées dans le texte.
P — précipitations annuelles en mm.
Ep — évapotranspiration potentielle annuelle en mm.
Ia — indice d'aridité = rapport de la somme des déficits mensuels du bilan hydrique à l'évapotranspiration potentielle annuelle.
Ih — indice d'humidité = rapport de la somme des surplus mensuels du bilan hydrique à l'évapotranspiration potentielle.
I — indice global = $Ih - 0{,}6\,Ia$.

effectué sur des précipitations réellement tombées, et non plus sur des moyennes, permet de distinguer deux sortes de stations :

— celles où un surplus n'apparaît presque jamais : c'est la *zone aride* (au Maroc on y note les stations de : Marrakech — Taroudannt — Guercif);

— celles où un surplus n'apparait pas tous les ans : c'est la *zone semi aride* (à Oujda par exemple, 1 année sur 2 seulement), en moyenne bénéficie d'un surplus.

La concentration des pluies, en un petit nombre de jours situés durant les mois à faible évapotranspiration potentielle, est à cet égard plus importante que la quantité globale de pluies annuelles.

Quoiqu'il en soit, dans l'un et l'autre type de région, l'inexistence ou l'irrégularité interannuelle des infiltrations sur la plaine elle-même, mises ci-dessus en évidence, n'assureraient pas la permanence d'une réserve souterraine. Pour expliquer que des nappes phréatiques non négligeables pour la mise en valeur des plaines agricoles existent néanmoins en zone aride ou semi aride, il faut faire appel à la notion de ressources allogènes. L'intérêt de ces ressources formées en des zones plus humides (proches montagnes ou zone lointaine plus tempérée) bien connu en hydrologie superficielle (cas du Nil par exemple) l'est moins en ce qui concerne les nappes aquifères.

Les eaux, soustraites à l'évaporation en dehors de la zone aride, participent à l'alimentation des nappes phréatiques de deux façons :

a) Si elles sont superficielles (eaux de ruissellement) elles peuvent s'infiltrer en plaine soit sur les matériaux grossiers des cônes de déjection, soit sur les limons cultivés où l'on épand les eaux de crues. Les procédés de réalimentation artificielle des nappes ne font que systématiser et aménager les processus de réalimentation naturelle.

b) Si les ressources allogènes se sont infiltrées en montagne sur des roches fissurées, principalement calcaires, mais aussi sur des roches à perméabilité en petit, sableuses ou gréseuses, (le coefficient d'infiltration sur ces deux types de roches est parfois si élevé que les talwegs inscrits sur leurs affleurements coulent rarement) elles peuvent en arrivant au niveau de la plaine, selon leur niveau hydrostatique et la structure de la roche magasin, suivre trois directions :

*b*1) Exsurger sous forme de grosses sources de piémont dont une partie se réinfiltrera dans les alluvions de la plaine.

*b*2) Continuer leur cheminement dans la même formation, et se mettant en charge sous des formations imperméables devenir des nappes profondes aux exutoires lointains.

*b*3) S'aboucher aux alluvions soit directement, soit par l'intermédiaire d'un relai hydraulique, soit encore à la faveur d'une structure faillée qui réalise un seuil hydraulique; les différences de perméabilité et de régime de circulation entre la roche aquifère primaire (roche mère) et les alluvions (magasin secondaire) occasionnent dans la nappe phréatique des anomalies piézométriques, chimiques, thermométriques qui permettent de déceler et de localiser ces phénomènes d'alimentation latérale.

Au Maroc, les grandes plaines sont toutes situées en zone aride ou semi aride (2) sauf le Nord du Rharb et les dépressions du Rif Occidental (voir la carte de situation ci-dessous). Par contre, les montagnes du Rif et du Moyen Atlas sont très pluvieuses : il tombe plus de 2 m d'eau nes zones du Rif, plus de 800 mm sur la plus grande partie du Moyen Atlas, et plus de 500 sur une grande partie du Haut Atlas.

Aussi les nappes phréatiques font elles toutes intervenir dans leur bilan hydraulique, au chapitre des apports, l'une ou l'autre de ces modalités d'alimentation latérale — dans des proportions variables, mais importantes par rapport au processus d'alimentation par infiltration directe.

Au Maroc Oriental, où l'aire de sécheresse remonte très au Nord par suite de l'écran climatique du Moyen Atlas et du Rif, plusieurs beaux exemples de ce type sont à signaler :

— *Dans la plaine des Triffa* (³) située en zone semi aride (Berkane : $P = 350$, $Ep = 915$, $I = -37{,}0$) 40% des apports soit 700 l/s sont vraisemblablement dus à une alimentation latérale souterraine de la nappe phréatique à partir de la « nappe » profonde des calcaires du Lias du massif des Beni-Snassene orientaux (à Aïn-Almou $P = 571$). Ce pourcentage est important surtout si on le compare à celui des infiltrations des pluies tombées sur la plaine elle-même : 28% de l'actif du bilan (coefficient d'infiltration : 6 à 7%). L'apport latéral, théoriquement possible d'après le bilan de la nappe du Lias, est suggéré par la carte des températures : l'eau de la nappe phréatique est à une température supérieure de 6 à 8° à la température moyenne du lieu, dans un certain nombre de puits alignés selon la direction régionale des failles de distension.

— *Dans la plaine des Anngad*, plaine semi désertique située entre la chaîne des Beni-Snassene au Nord et la chaîne des Zekkara au Sud (⁴) (Oujda : $P = 342$, $Ep = 872$, $I = -36.5$) l'infiltration des pluies ne représente que 15% de l'alimentation de la nappe phréatique (coefficient d'infiltration : 7%) et l'apport des eaux des calcaires du Lias de la zone des Beni-Snassene orientaux (flanc Sud) et surtout de la zone des horsts (Bou-Bekere : $P = 465$) par le relai hydraulique d'une traînée de basaltes et de cinérites de 25 km de longueur représentent un apport allogène de 500 à 700 l/s soit 50 à 70% de l'alimentation de la nappe phréatique.

Cet apport est ici suggéré par la forme déprimée des courbes de la nappe phréatique, au point d'abouchement, par les débits spécifiques élevés de cette zone (plus de 30 l/s/m) et par la ressemblance chimique des eaux de cette zone avec celles du as de la zone des horsts.

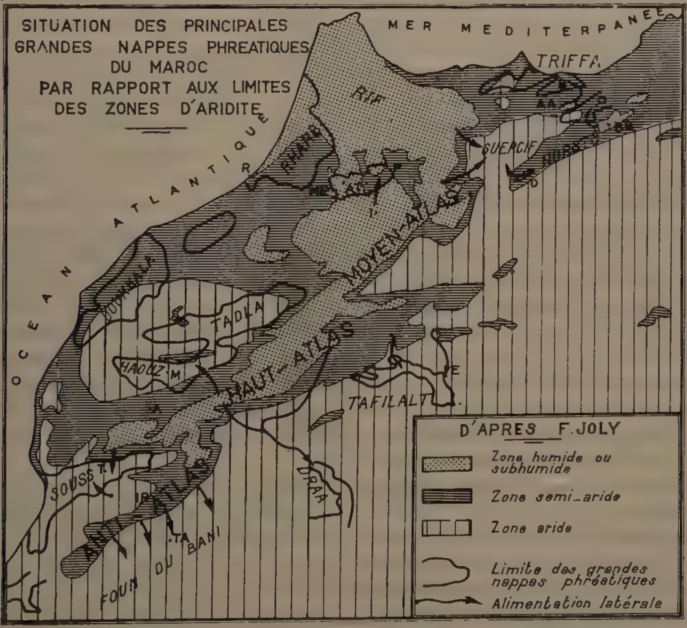

Fig. 1 — *AA* = Aïn Almou — A = Amizmiz — *B* = Berkane — *BB* = Bou Beker — *D* = Debdou — *E* = Erfoud — *F* = Fès — *G* = Guercif — *I* = Ifrane *Ir* = Irherm — *M* = Marrakech — *Me* = Meknès — *O* = Oujda — *R* = Rabat — *T* = Taroudant — *Ta* = Tata — *At* = Aïn Taoujdate.

— *Dans la région de Guercif* (5) où les conditions d'aridité très dures malgré la latitude (*P* = 192, *Ep* = 985, *I* = – 48,8) devraient interdire la constitution de réserves souterraines, on note au Sud Est (plaine de Mahrouf) une petite nappe phréatique dans des limons; la qualité chimique des eaux se rapproche de celle des eaux des calcaires du Lias de la Gaada de Debdou (*P* = 457). La tectonique cassante révélée par géophysique et sondages permet un abouchement de ces calcaires avec les alluvions de la plaine.

— *Au Nord Ouest* de Guercif (plaine du Jel) la découverte récente d'une nappe phréatique peut s'expliquer par les infiltrations dans les conglomérats pliocènes des eaux des Oueds Meloullou et Msoun nés tous deux dans des montagnes qui sont parmi les plus arrosées du Maroc (pluviométrie supérieure à un mètre).

— *Le plateau de Fès-Meknès* situé à la limite des zones subhumide (Fès : *I* = – 18,3) semi aride (Aïn Taoujdate : *I* = – 25,0) est la région agricole du Maroc la plus riche en eaux souterraines. Les eaux infiltrées massivement sur les calcaires liasiques du causse moyen atlasique (Ifrane : *P* = 1 101 mm, *Ep* = 645, *I* = 84,8), ressortent en grosses sources de piémont qui se réinfiltrent en partie, alimentent latéralement la nappe phréatique des calcaires lacustres comme en témoigne l'analogie chimique des sources des calcaires du Lias et des premières sources des calcaires lacustres, et enfin forment une nappe profonde, exploitée par plusieurs forages artésiens et ressortant en sources thermales au front des nappes rifaines. Mais dans ce domaine plus humide, la proportion des infiltrations des pluies dans le total des apports à la nappe phréatique (coefficient d'infiltration sur les calcaires lacustres : 25 %) est bien supérieure à ce qu'elle est dans les autres plaines du Maroc (6).

Il en est de même dans *le Rharb* où une nappe phréatique stagnante est uniquement alimentée par les pluies (Souk el Arba du Rharb : *I* = – 13,1) mais où les nappes profondes ont leur origine dans des zones bordières un peu plus sèches mais beaucoup plus perméables (*Mamora*, cône de déjection du Sebou).

— *Au Haouz* (7) dont la capitale Marrakech est considérée comme le type de la zone aride du Maroc (*P* = 242, *Ep* = 1 015, *I* = – 45,7) il ne semble pas, sauf peut être dans le Haouz oriental, qu'il y ait de nappes profondes importantes ni d'alimentation latérale de la nappe phréatique par des nappes formées dans l'Atlas (Amizmiz, *P* = 481, *I* = – 26,0) mais l'alimentation essentielle de la nappe résulte de l'infiltration des eaux de crue des Oueds atlasiques selon leur cours, principalement au débouché dans la plaine. Cette infiltration massive provoque une remontée importante du niveau de la nappe qui se propage en s'amortissant, telle une vague phréatique, à la vitesse de 200 m/j. La réalimentation à la verticale par return-flow sur les surfaces irriguées n'est pas négligeable.

— *Avec le Tafilalt* (8) on passe au Maroc présaharien (à la limite de la zone hyper-aride) (Erfoud, *P* = 80, *Ep* = 159, *I* = – 5,7) la nappe phréatique doit également tout aux eaux superficielles formées en montagne, mais l'infiltration par épandage massif des eaux de crue sur les limons des palmeraies est prépondérante dans l'alimentation de la nappe, tandis que les infiltrations par les lits des oueds représentent 20% seulement et l'infiltration des pluies moins de 2%.

— *Dans le Souss* (9) également situé au Sud du Haut Atlas, mais ouvert sur la mer (Taroudannt : *P* = 212, *Ep* = 73, *I* = – 46,3) il y a à la fois infiltrations des crues de l'Oued Souss dans le cône de déjection de l'Aoulouz et alimentation latérale de la nappe phréatique par les circulations karstiques des calcaires géorgiens de l'Anti-Atlas, et par les nappes des calcaires crétacés du Haut-Atlas. Ces zones d'abouchements sont mises en évidence par des anomalies de la température des eaux de la nappe phréatique.

— *A l'extrême Sud du Maroc* (10) malgré des conditions atmosphériques hyper-arides (Tata : *P* = 77, *Ep* = 1289, *I* = – 56,3) les palmeraies des *foums du Bani* sont alimentés en eau par l'apport aux alluvions des *feija* de la nappe des calcaires géorgiens de l'Anti-Atlas qui malgré une pluviométrie très faible (Irherm : $P = 186$) ne présente que des variations interannuelles atténuées grâce à l'immensité de la surface de réception des calcaires très diaclasés et à leur volume d'accumulation.

Au cours de cette rapide revue des conditions d'alimentation des grandes nappes préatiques du Maroc, s'est imposée la notion de bassin hydrogéologique, dans le cadre duquel s'opère la compensation entre le bilan hydrique déficitaire d'une région de plaine aride ou semi aride et les surplus d'eau superficielle ou souterraine de la montagne voisine. Dans un pays à structure relativement complexe comme le Maroc, les limites des bassins hydrogéologiques sont plus restreintes que celles des bassins versants hydrologiques. Il en résulte une étroite interpénétration des bassins synclinaux et des chaînes anticlinales, et de nombreuses structures favorables à des relais hydrauliques; ces deux facteurs liés à la grande surface d'affleurement dans des montagnes relativement bien arrosées, des calcaires géorgiens, liasiques, bajobathoniens et crétacés, sont éminemment favorables à une relative richesse des plaines marocaines en eaux souterraines : «l'exploitation des eaux souterraines par gravité ou par exhaure fournit environ 22 m^3/s, soit plus du tiers du débit pérenne des cours d'eaux superficiels» (11).

BIBLIOGRAPHIE

(1) C. W. Thornthwaite. — An approach toward a rational classification of climate. *Geogr. Rev.* 1948, pp. 55-94.

(2) F. Joly. — Étude des indices de Thornthwaite pour quelques stations du Maroc. *Ann. du Serv. de Ph. du Globe TXVIII*, 1958, pp. 119-128.

(3) F. Mortier. — Bilan de la nappe phréatique de la plaine des Triffa. *C.R. du Congrès U.G.G.I. (A.I.H.S.) Toronto*, 1957, *T II* pp. 115-125.

(4) F. Mortier. — Recherches hydrogéologiques dans les plaines du couloir Oujda-Taza (en cours d'impression).

(5) F. Mortier et M. Fellahi. — Découverte de nappes aquifères dans la région de Guercif (Maroc oriental). *Bull. Mines et Géologie*, N° 3 1958.

(6) J. Margat. — La nappe phréatique du bassin de Fès-Meknès. Bilan de nos connaissances actuelles. *Var. Sc.* n° 7. Soc. Sc. not. Maroc, Rabat 1955.

(7) R. Ambroggi et G. Thuille. — Haouz de Marrakech. *Notes et Mém. Service Géol. Maroc* n° 97, 1952, pp. 223-233.

(8) J. Margat. — Notice de la carte hydrogéologique du Tafilalt. *Notes et Mém. Serv. Géol. Maroc* n° 150 bis (sous presse 1961).

(9) R. Ambroggi et J. Bourgin. — Vallée du Souss. *Notes et Mém. du Serv. Géol. Maroc* n° 97, 1952, pp. 269-284.

(10) R. Ambroggi et G. Choubert. — Anti-Atlas et vallée du Dra id, pp. 324-335.

(11) R. Ambroggi. — Les recherches d'eau au Maroc et le Centre des Etudes Hydrogéologiques. *Bull. Mines et Géologie*. 1-1-1958.

AN ANALYSIS OF RESERVOIR CAPACITY REQUIREMENTS FOR CONJUNCTIVE USE OF SURFACE AND GROUNDWATER STORAGE

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Abstract

Maximum development of water resources requires conjunctive utilization of surface and groundwater reservoirs. To do so, one has to determine the amount of surface storage to be provided, and to establish a pattern for allocating the available water to surface and to groundwater storage.

A conceptual framework is provided for the solution of these problems, using a method of analysis termed "dynamic programming".

The operational problem is considered first and the allocation to each of the two kinds of storage is attempted. The allocation problem is shown to result into an "all or nothing" proposition, i.e., all available water should be stored in surface storage or in the aquifer, depending on the state of the system.

The surface storage capacity is determined by optimizing the total net benefit over the reasonable economic life of the project, using a proper discount rate for selected surface storage capacities in a logical range. A mathematical model is set up, solvable by the use of high speed digital computers, so that particular situations may be solved for the optimal reservoir capacity.

Résumé

Le développement maximum des ressources en eau exige l'utilisation des réservoirs superficiels en conjonction avec les réservoirs d'eau souterraine. Pour atteindre ce but, il faut se décider sur la capacité du réservoir superficiel qu'on doit construire, et il faut établir un procédé d'allocation d'eau disponible à ce réservoir et au réservoir souterrain. Pour résoudre ces problèmes, un cadre théorique est fourni, employant une méthode d'analyse appelée «dynamic programming».

On considère d'abord le problème de l'allocation et on essaye d'allouer l'eau disponible à chacun des deux réservoirs. Il est prouvé que ce problème nous mène à la conclusion de détourner toute la quantité d'eau au réservoir superficiel ou au réservoir souterrain, selon l'état du système.

La capacité du réservoir superficiel est déterminée suivant l'optimum du profit net total dérivé pendant la durée d'ammortissement du projet, employant un cours d'escompte convenable et des capacités choisies dans des limites logiques. Un modèle mathématique est dressé, qui peut être résolu par l'emploi de calculateurs électroniques rapides, afin que des situations particulières puissent être résolues et afin que la capacité optimum des réservoirs superficieux puisse être déterminée.

1. Introduction

Water resources, their quality and availability, are a limiting factor in the development of most arid and semi-arid regions. The optimum utilization of these resources is essential for the establishment of sound economic and social structures in these regions.

There are two important objectives to be attained in the development of water resources: 1) a dependable supply of water to satisfy a variety of needs (irrigation, production of hydro-electric power, municipal and industrial uses, recreation, etc.) and 2) protection of low lands against flooding. To attain these objectives, water must be stored at times when inflow less permissible outflow to a basin exceeds demands.

The use of surface reservoirs to attain these two objectives, water supply and flood control, is a well established practice. Groundwater aquifers also have been long recognized as important sources of water. However, subsurface reservoirs have been managed until recently with almost complete disregard to surface storage. Only in the last two decades have worthy attempts been made to establish the inter-relation between surface and groundwater ([1, 10]) and to offer a rational foundation to the utilization of the subsurface storage space ([2, 17]) for resource development purposes.

As more information is gathered on groundwater hydrology ([18]), and as demands on the potential supply increase, the question of optimum use policy for groundwater resources is brought into sharper focus ([3, 16]). It seems now appropriate, therefore, to approach the broad problem of optimum utilization of a water resource where a system of surface reservoirs may be operated in conjunction with groundwater aquifers

2. THE STORAGE ALLOCATION PROBLEM

In many geographic areas where water resource development is contemplated, there exist groundwater storage basins whose capacity can be utilized, particularly for carryover storage for long cyclic variations in runoff.

Where this situation obtains, two questions must be answered by the water resource engineer: *first*, how should available water be allocated operationally to surface or groundwater storage; *second*, how much surface storage should be provided. In this section the first problem is solved. In a later section the second problem is treated.

Let it be postulated that the average benefits (however defined) from consumptive use, not including storage costs, are known for each time interval. This implies that the demand for water is also known for the same time interval. The two questions may then be resolved by minimizing the cost of storage and subsequent withdrawal to meet demand according to some optimum policy.

The following nomenclature is adopted. Let x_i be the monthly demand for water varying from month to month but, by postulate, the same for a given month in any year, y_i be the inflow during any month (a stochastic function) and s_i be the water available for storage. Note that s_i may be positive or negative, the latter representing a withdrawal requirement to meet demands.

Let q_i and g_i represent the quantities of water in surface and groundwater storage at the end of the i^{th} month respectively while Q and G are the corresponding maximum storage limits.

Finally, s_{i1} represent the quantity from s_i which may be allocated to surface storage and s_{i2} represent the quantity allocated to groundwater storage with corresponding costs c_{i1} and c_{i2}. Then the problem is to select s_{i1} and s_{i2} such that:

$$C_i = \min\,[c_{i1}(s_{i1}, q_i), + c_{i2}(s_{i2}, g_i)] \tag{1}$$

subject to:

$$s_{i1} + s_{i2} = s_i;$$

and

$$0 \leqslant q_i \leqslant Q$$
$$0 \leqslant g_i \leqslant G$$

Distinction must be made at this point between costs incurred by allocation of storage or withdrawal to the approprate storage unit. For example, for a given surface reservoir of peak capacity Q, the cost of this reservoir is fixed and unaffected by whether a particular volume of water is stored there or not. Similarly if the reservoir level is q_i, the evaporation losses incurred by a decision to store s_{i1} can only include those due to the small increment in surface area of the reservoir. Likewise the cost of removal from storage should be charged at the time of withdrawal, not at the time of storage, since it is possible that water could go into storage for the purpose of raising water levels for energy conservation reasons with no intent of subsequent withdrawal.

If desired, hydro-electric benefits due to water levels may be introduced here as a "negative cost" provided that the consumptive use demands x_t include any water released for power production purposes only and subsequently wasted. Here again, for any given installation, the capital costs are fixed and are not affected by the allocation of a particular quantity s_t.

The differential costs of storing in or removing water from a surface reservoir thus are essentially those operational costs for the reservoir which are increased by the act of storing or removing. These are essentially zero since operating personnel and equipment will be present in any event. The major differential cost of removing water from subsurface storage will be the pumping cost.

A verbal equation for the important differential costs would be:

$$\text{Differential costs} = \min \left\{ \begin{matrix} \text{flood risks} - \text{hydroelectric} \\ \text{benefit} + \text{pumping costs} \end{matrix} \right\} \qquad (2)$$

Flood risk is primarily a function of the reservoir level (or q_t) and the probable inflow (y_t) for the particular period. Hydroelectric benefit is also primarily a function of reservoir level (q_t) while pumping costs depend mainly upon the pumping lifts, in turn a function of g_t, the groundwater storage level.

Thus it is seen that the differential costs incurred in storing water above or below ground depend primarily upon g_t, q_t and y_t (x_t fixed). Under these conditions it may be expected that the water available for storage, s_t, will be entirely allocated to either surface or groundwater storage.

3. OPTIMUM SURFACE STORAGE CAPACITY

The second problem concerns the amount of surface storage to be provided for conjunctive operation. With the knowledge that the allocation of the water available in a particular small period of time s_t, will be entirely to one or to the other, this question may be readily solved by "dynamic programming" (4, 5, 7, 8, 9).

From preliminary observations the actual capacity of the groundwater reservoir G may be established and will not vary. Thus the principal variables are Q_t, q_t, and g_t. The probable inflow y_t and the demand x_t are presumed known. Consider the system to consist of one surface reservoir and a groundwater aquifer to be operated conjunctively for n consecutive time periods. At each of the n stages of operation, a net benefit $V_t(q_t, g_t)$ is derived as a function of the state of the system. It is desired to select q_t and g_t so as to maximize the overall benefit

$$B = \max \left\{ \sum_{t=1}^{n} V_t(q_t, g_t) \right\}$$

subject to

$$\begin{aligned} 0 \leqslant q_t \leqslant Q, \\ 0 \leqslant g_t \leqslant G. \end{aligned} \qquad (3)$$

The dynamic programming solution of equation (3) proceeds by assuming first that only one time interval or stage remains in total operational period. With this one stage remaining, the benefit derived from the system in that state will be the maximum difference between returns and costs when the available water is allocated to either surface or to groundwater storage. Since neither g_t nor q_t are known for this final period, we will define $f_1(q_1, g_1)$ to be the maximum benefit for all possible values of g_1 and q_1 in the ranges prescribed by equation (3). Mathematically this is expressed as

$$f_1(q_1,g_1) = \max. \begin{cases} a: \text{returns less costs for surface storage or removal.} \\ b: \text{returns less costs for groundwater storage or removal.} \end{cases}$$

$$\begin{aligned} 0 \leqslant\, & q_1 \leqslant Q \\ 0 \leqslant\, & g_1 \leqslant G \end{aligned} \tag{4}$$

In general, during any time interval, an allocation s_i to surface storage results in a benefit for alternative (*a*):

$$B_{ai} = v_i(x_i) + h_i(x_i, q_i) - c_{fi}(q_i + s_i) - c_{ai}(s_i) - F_a \tag{5}$$

where

$v_i(x_i)$	is the return from the consumptive use of water;
$h_i(x_i, q_i)$	is the return from hydro-electric energy produced by releasing x_i ac-ft of water at a head determined by the amount q_i stored in the reservoir;
$c_{fi}(q_i + s_i)$	is the increase in the flood hazard when the flood control storage space is reduced by s_i;
$c_{ai}(s_i)$	is the cost of storing in the surface reservoir (operation charges);
F_a	includes any other costs, fixed or otherwise.

If s_i is allocated to groundwater, the benefits for alternative (*b*) are:

$$B_{bi} = v_i(x_i) + h_i(y_i,q_i) + k_i s_i \left(H - \frac{g_i}{\delta A}\right) - c_{bi}(s_i) - F_b \tag{6}$$

where

$v_i(x_i)$	is defined as before;
$h_i(y_i, q_i)$	is the return from hydro-electric energy produced by releasing the amount y_i at a head determined by q_i;
k_i	is the price of energy required from pumping from the aquifer (note that here s_i is negative);
H	is the maximum economic lift;
σ	is the specific yield of the aquifer;
A	average cross-sectional area of the aquifer;
$c_{bi}(s_i)$	is the cost of aquifer recharge operation;
F_b	includes any other cost, fixed or otherwise, connected with aquifer recharge.

It is to be noted that B_{ai} considers possible returns from hydro-electric power production only to the extent that the demand x_i is released through the turbines, whether s_i is positive or negative. B_{bi}, on the other hand, considers that the entire inflow y_i may yield hydroelectric benefits, whether there is water available for aquifer recharge or not.

Substituting expressions (5) and (6) into equation (4) for $i = 1$ we obtain

$$f_1(q_1,g_1) = \max \begin{cases} a: v_1(x_1) + h_1(x_1,q_1) - c_{f1}(q_1 + s_1) - c_{a1}(s_1) - F_a \\ b: v_1(x_1) + h_1(y_1,q_1) + k_1 s_1 \left(H - \dfrac{g_1}{\delta A}\right) - c_{b1}(s_1) - F_b \end{cases} \tag{7}$$

$$\begin{aligned} 0 \leqslant\, & q_1 \leqslant Q \\ 0 \leqslant\, & g_1 \leqslant G \end{aligned}$$

Equation (7) gives the maximum benefit and the allocation of s_1 for the last period. If two stages remain in the operation, the principle of optimality (4) requires that if the overall benefit is to be a maximum, the allocation in the last stage must also be optimal whatever the decision at the next to last stage may be. Therefore

$$f_2(q_2,g_2) = \max \begin{cases} a: B_{a2} + \left(\dfrac{1}{1+r}\right) f_1[q_1 - e_2(q_2) + s_2, g_1] \\ b: B_{b2} + \left(\dfrac{1}{1+r}\right) f_1[q_1, g_1 + s_2 - \epsilon_2(g_2)] \end{cases} \tag{8}$$

$$0 \leqslant q_2 \leqslant Q$$
$$0 \leqslant g_2 \leqslant G$$

Here $e_i\,(q_i)$ and $\epsilon_i\,(g_i)$ are respectively, evaporation losses and unrecoverable seepage due to surface storage, and unrecoverable subsurface outflow. B_{a2} and B_{b2} are given by the expressions (5) and (6), while f_i is defined by equation (7). The quantity r is defined as the rate of discount per time interval.

In general, progressing through three, four, ..., n, stages remaining, there results the recursive relationship:

$$f_n(q_n,g_n) = \max \begin{cases} a: B_{an} + \left(\dfrac{1}{1+r}\right) f_{n-1}[q_{n-1} - e_n(q_n) + s_n, g_{n-1}] \\ b: B_{bn} + \left(\dfrac{1}{1+r}\right) f_{n-1}[q_{n-1}, g_{n-1} + s_n - \epsilon_n(g_n)] \end{cases} \tag{9}$$

$$0 \leqslant q_n \leqslant Q$$
$$0 \leqslant g_n \leqslant G$$

The recurrence relationships defined by equation (9) is solved for a discrete set of (q_i, g_i) by holding g_i constant at a particular value and proceeding with the normal dynamic programming solution on a digital computer for the range of values of q_i. The magnitude of g_i is then changed and the process repeated. This results in a three dimensional matrix $k \times m \times n$ where k is the number of q increments in the range, m is the number of g increments and n is the number of time intervals being studied. Table 1 demonstrates this matrix for a particular n.

At each point in the matrix there is given the optimum policy (i.e., surface storage or groundwater storage) and the resulting benefit for the *remaining* stages. Knowing the optimal policy for the point (q_i, g_i) the change in reservoir conditions is determined by the additions or depletions represented by that decision. Note that the increment of q_i and g_i must be equal. They must also be equal to the smallest quantity of water worth considering in the analysis so that matrix points will correspond to discrete units in all parts of the analysis. Another way of stating it is that given particular values of k and m, the time intervals must be selected to be long enough so that quantities s_i, e_i, etc., can be expressed with reasonable accuracy as integer multiples of Q/k and G/m.

It may also be noted that a time lag intervening between the recharge operation and its subsequent effect on average pumping levels can be taken into account by replacing s_n in alternative b of equation (9) by s_{n-1}, s_{n-2} or s_{n-3}, as the appropirate lag is one, two or three time intervals.

The foregoing analysis was made for a particular surface reservoir of capacity Q (the upper limit on q_i in equation (3)). To determine the optimum Q it will be necessary to repeat this analysis for additional values of Q. Three or four values of Q in the range $0 \leqslant Q \leqslant Q_{max}$ may be selected judiciously. Q_{max} may be determined by queuing theory [11] or other methods [13]. This will give the general form of the optimum net benefit function so that the optimum reservoir capacity Q_1 can be found with sufficient accuracy with one or two more trial values.

Note that the values of q_n and g_n are the current or initial reservoir conditions and are specific values. Consequently only one decision and its corresponding benefit need be taken for each value of n in the three dimensional matrix. Thus for each trial value of Q there are only n (*a*) or (*b*) decisions and one net optimum benefit, f_n, to be retained. This will simplify the computational aspects of the problem.

There remains the problem of properly estimating the expected value of the inflow y_t. Several methods are available for the extrapolation of existing hydrological data ([12]). Unusually large flows or exceptionally low ones may be estimated by the statistical theory of extreme values ([6]). Monte Carlo techniques ([14]) may be used to derive synthetic hydrographs ([15]). Other methods may be suitable for different local conditions.

4. SUMMARY

Maximum development of water resources requires conjunctive utilization of surface and groundwater reservoirs. To do so, one has to determine the amount of surface storage to be provided, and to establish a pattern for allocating the available water to surface and to groundwater storage.

The operational problem is considered first and the allocation to each of the two kinds of storage is established. The solution of this problem is based on the postulate that the demand during a short period of time is known, and that the inflow during the same period of time can be estimated with some degree of probability. The allocation problem is shown to result in an ''all or nothing" decision depending on the state of the system.

The surface storage capacity is determined by optimizing by dynamic programming the total net benefit over the reasonable economic life of the project, using a proper discount rate for selected surface storage capacities in a logical range.

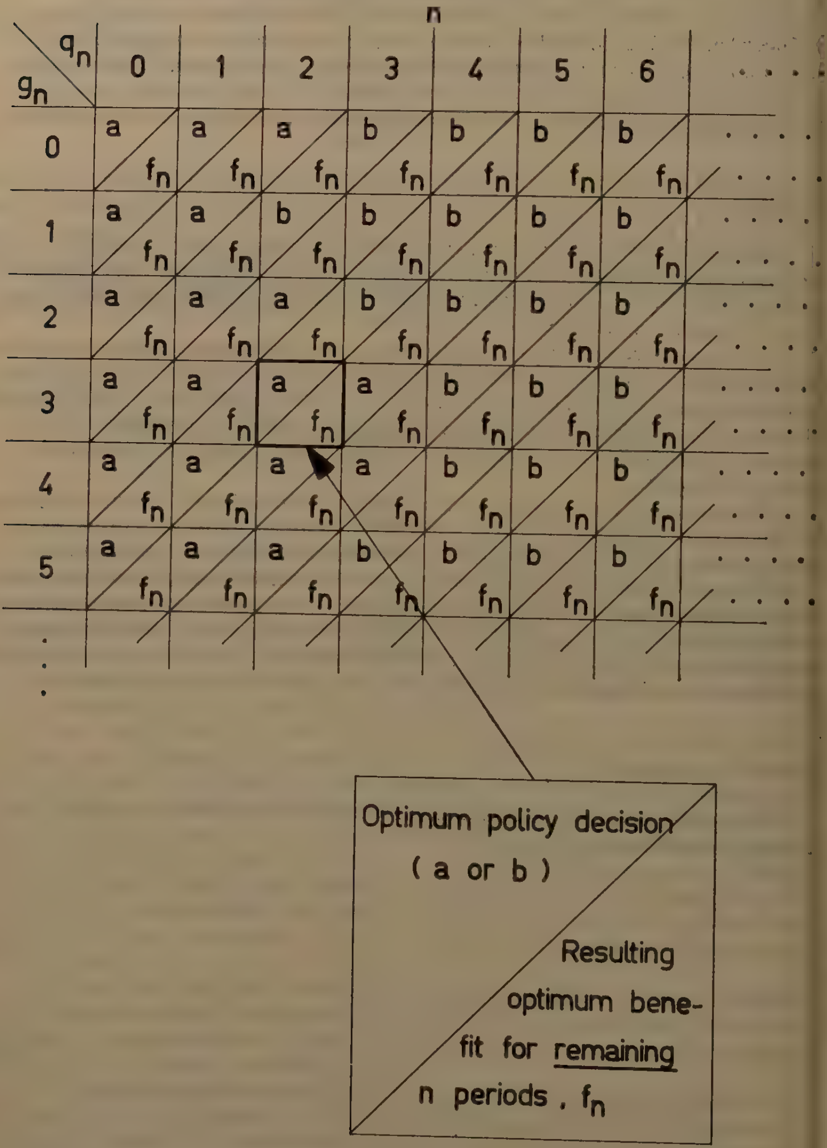
This paper describes a mathematical model, solvable by the use of high speed digital computers, by which particular situations may be solved for the optimal reservoir capacity. An actual solution is obtainable for any situation where the required data, inflow probabilities, demands, probable benefits, etc., are known. The accuracy of the solution will depend primarily upon the accuracy of such information.

5. ACKNOWLEDGMENT

This work was accomplished under a research grant by the University of California Water Resources Center.

TABLE 1

Matrix of optimum policy decisions and resulting optimum benefits for remaining n periods


Optimum policy decision
(a or b)
Resulting optimum benefit for remaining n periods , f_n

g_n \ q_n (n)	0	1	2	3	4	5	6	. . . .
0	a f_n	a f_n	a f_n	b f_n	b f_n	b f_n	b f_n	. . . .
1	a f_n	a f_n	b f_n	b f_n	b f_n	b f_n	b f_n	. . . .
2	a f_n	a f_n	a f_n	b f_n	b f_n	b f_n	b f_n	. . . .
3	a f_n	a f_n	a f_n	a f_n	b f_n	b f_n	b f_n	. . . .
4	a f_n	a f_n	a f_n	a f_n	b f_n	b f_n	b f_n	. . . .
5	a f_n	a f_n	a f_n	b f_n	b f_n	b f_n	b f_n	. . . .
. . .								

REFERENCES

(1) Ackerman, E.A., and G.O.G. Löf, *Technology in American Water Developmet*, The John Hopkins Press, Baltimore, xv + 710 pp., 1959.

(2) Banks, H.O., Utilization of Underground Storage Reservoirs, *Transactions American Society of Civil Engineers*, 118: 220-234, 1953.

(3) Baumann, P., Basin Recharge, *Transactions, American Society of Civil Engineers*, 122: 458-473,1957.

(4) Bellman, R., *Dynamic Programming*, Princeton University Press, Princeton, xxv + 342 pp., 1957.

(5) Buras, N., Application of Dynamic Programming Methods to Certain Watershed Management Problems, submitted for publication to *Agricultural Engineering*, 1960.

(6) Cumbel, E.J., *Statistics of Extremes*, Columbia University Press, New York, xx + 375 pp., 1958.

(7) Hall, W.A., and N. Buras, The Dynamic Programming Approach to Water-Resources Development, *Journal of Geophysical Research*, 66: 517-520, 1961.

(8) Hall, W.A., Aqueduct Capacity Determination under an Optimum Benefit Policy, submitted for publication to *Proceedings, American Society of Civil Engineers*, 1960.

(9) Hall, W.A., and N. Buras, Optimum Irrigation Practice Under Conditions of Deficient Water Supply, *Transaction American Society of Agricultural Engineering*, Vol. 4, No. 1, pp. 131-134, 1961.

(10) Khosla, A.N., Inter-relation of Surface and Ground Water with Special Reference to Arid Zones, *Desert Research*, Research Council of Israel Special Publication ≠ 2, Jerusalem, pp. 568-581, 1953.

(11) Langbein, W.B., Queuing Theory and Water Storage, *Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers*, vol. 84, paper ≠ 1811, 24 pp., 1958.

(12) Langbein, W.B., and C.H. Hardison, Extending Streamflow Data, *Proceedings, American Society of Civjl Engineers*, New York, vol. 81, separate ≠ 826, 13 pp., 1955.

(13) Moran, P.A.P., A Probability Theory of Dams and Storage Systems, *Australian Journal of Applied Science*, vol. 5, pp. 116-124, 1954.

(14) Sasieni, M., A. Yaspan and L. Friedman, *Operations Research*, John Wiley & Sons, Inc., New York, xi + 316 pp., 1959.

(15) Snyder, F.F., Synthetic Flood Frequency, *Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers*, vol. 84, paper ≠ 1808, 22 pp., 1958.

(16) Thomas, H.E., Essentials for Optimum Development of Ground-Water Resources, *Resources Development: Frontiers for Research*, Western Resources Papers, University of Colorado Press, Boulder, pp. 181-191, 1960.

(17) Thomas, R.O., General Aspects of Planned Ground Water Utilization, *Proceedings, American Society of Civil Engineers*, vol. 81, separate ≠ 706, 11 pp., 1955.

(18) Todd, D.K., *Ground Water Hydrology*, John Wiely & Sons, Inc., New York, xii + 336 pp., 1959.

DEVELOPMENT OF A KARST LIMESTONE SPRING IN GREECE

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ABSTRACT

A study has been made of the hydrogeology of the Lilaia group of springs on the north-west flank of Parnassos. It is planned to carry out experiments to determine how best the flow of the spring could be regulated. Such regulation may be achieved by pumping during the irrigation season to such an extent that the underground reservoirs in the limestone would be so depleted that the earlier portion of the winter infiltration would be stored underground and free flow from the spring would not recommence until the middle of the winter. The objective is to alter the discharge of the aquifers in time, though not in space.

The spring is supplied with groundwater from limestone aquifers, in part in the form of over-flow from a full aquifer and in part by almost immediate discharge after heavy rain. Yield data for the twenty years from 1933 to 1953 have been analysed it is planned to drill boreholes to determine the exact depth and permeability of the aquifer, as well as to make a trial pumping from the spring during summer and automn 1961 or 1962. From the data thus obtained, the size of a permanent pumping installation can be determined.

Agricultural, social and economic changes likely to be produced by such control of the spring discharge have been studied.

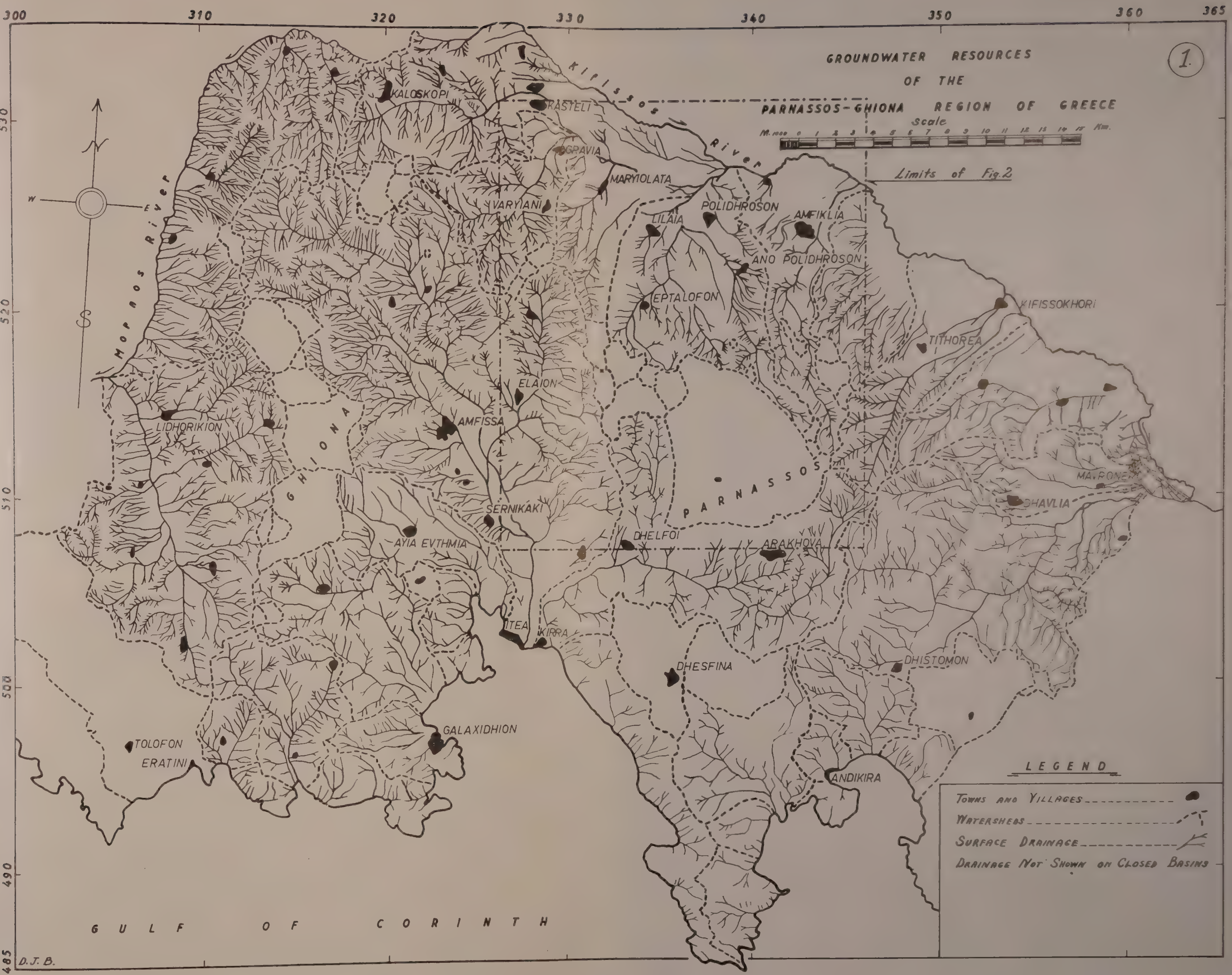
RÉSUMÉ

Une étude a été faite de l'hydrogéologie du groupe de sources de Lilaia sur le flanc N.E. du Parnasse. On se propose d'effectuer des expériences pour déterminer quelle est la meilleure mesure de régulation de ces sources. Une telle régulation peut être obtenue en pompant pendant la saison des irrigations avec une intensité telle que les réservoirs souterrains du calcaire seraient suffisamment rabattus pour que l'infiltration de la première partie de l'hiver soit emmagasinée souterrainement et que l'écoulement libre des sources ne recommence que vers le milieu de l'hiver. L'objectif est de modifier la décharge des nappes dans le temps mais non dans l'espace. La source est alimentée par l'eau souterraine de calcaires en partie comme trop plein d'une nappe remplie et en partie par une décharge quasi immédiate après une pluie abondante. Les délits durant vingt ans de 1933 à 1953, ont été analysés.

On se propose de faire des sondages pour déterminer la profondeur exacte et la perméabilité de la nappe, ainsi que pour faire un pompage d'essai de la source au cours des étés et des automnes de 1961 et 1962.

Des résultats obtenus, on déterminera la puissance de l'installation permanente de pompage.

Les modifications agricoles, sociales et économiques à provenir de ce contrôle du délit de la source ont été étudiées.



GROUNDWATER RESOURCES
OF THE
PARNASSOS-GHIONA REGION OF GREECE
1.
Scale
M. 1000 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 Km.
Limits of Fig. 2
300
310
320
330
340
350
360
365
530
520
510
500
490
485
N
S
W
E
Kifissos River
Mornos River
KALOSKOPI
KASTELI
GRAVIA
MARYIOLATA
VARYIANI
LILAIA
POLIDHROSON
AMFIKLIA
ANO POLIDHROSON
EPTALOFON
KIFISSOKHORI
TITHOREA
ELAION
AMFISSA
LIDHORIKION
GHIONA
PARNASSOS
MAVRONERI
DHAVLIA
SERNIKAKI
AYIA EVTHMIA
DHELFOI
ARAKHOVA
ITEA
KIRRA
DHESFINA
DHISTOMON
GALAXIDHION
TOLOFON
ERATINI
ANDIKIRA
GULF OF CORINTH
D.J.B.
LEGEND
Towns and Villages
Watersheds
Surface Drainage
Drainage Not Shown on Closed Basins

Fig. 1

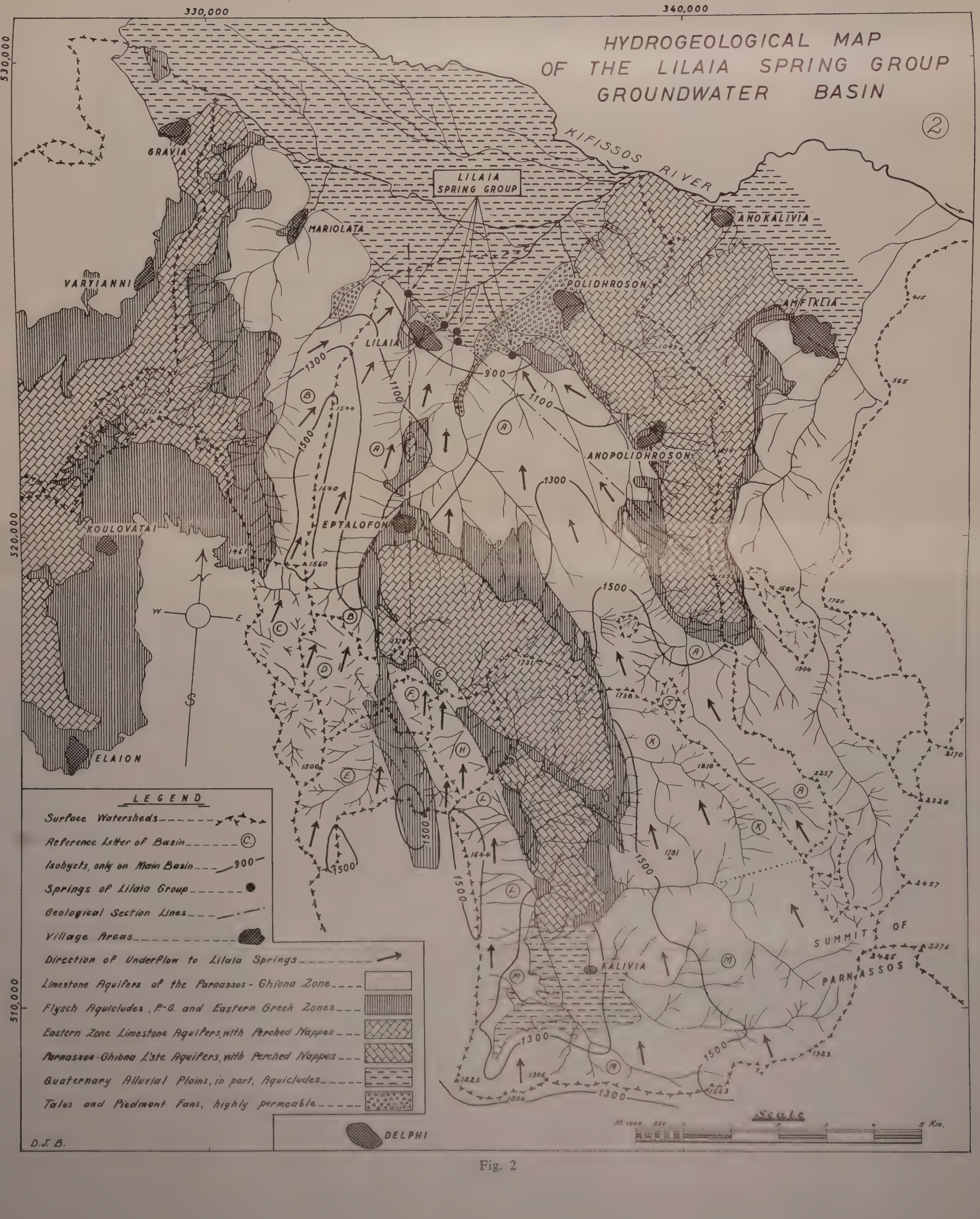

HYDROGEOLOGICAL MAP
OF THE LILAIA SPRING GROUP
GROUNDWATER BASIN
②
330,000
340,000
530,000
520,000
510,000
KIFISSOS RIVER
LILAIA SPRING GROUP
GRAVIA
MARIOLATA
VARYIANNI
LILAIA
POLIDHROSON
ANOKALIVIA
AMFIKLIA
ANOPOLIDHROSON
EPTALOFON
KOULOVATAI
ELAION
KALIVIA
SUMMIT OF PARNASSOS
DELPHI
W
E
S
LEGEND
Surface Watersheds
Reference Letter of Basin
Isohyets, only on Main Basin
Springs of Lilaia Group
Geological Section Lines
Village Areas
Direction of Underflow to Lilaia Springs
Limestone Aquifers of the Parnassos - Ghiona Zone
Flysch Aquicludes, P-G. and Eastern Greek Zones
Eastern Zone Limestone Aquifers, with Perched Nappes
Parnassos-Ghiona L'ste Aquifers, with Perched Nappes
Quaternary Alluvial Plains, in part, Aquicludes
Talus and Piedmont Fans, highly permeable
Scale
M. 1000 500
5 Km.
D.J.B.

Fig. 2

1. INTRODUCTION AND GEOGRAPHICAL SETTING OF THE LILAIA SPRING GROUP

In the course of the current investigation into the groundwater resources of the karstic limestones of Greece undertaken by the Institute for Geology and Subsurface Research of the Government of Greece in co-operation with the Special Fund of the United Nations, it became clear that in many regions there was abundant groundwater issuing as springs, but that much of this water was wasted since most of it was discharged too quickly after the rain and so too early in the year for irrigation use. The water was there, but it was necessary to alter its temporal distribution, reducing spring yields in winter and early spring, and increasing them in summer and early autumn.

Considering also the difficulty of locating high-yielding boreholes in the karstic limestones of Greece, it seemed advisable that investigations should be made on methods of obtaining effective control of yield at points of natural issue of groundwater from the limestones. At such points, it was certain that the water was present; the possibility of not finding water was eliminated. If the yield could be beneficially controlled, then such control would constitute "a successful and efficient development of groundwater resources in limestone terrain" as demanded by the Project.

The Parnassos-Ghiona area, covering some 1774 square kilometers (as shown in fig. 1), was the first region to be investigated. The Lilaia Group of Springs was made the object of a special detailed investigation (as decided by numerous factors, including the existence of adequate discharge data); their recharge areas were also studied and the limits of the groundwater basin may be seen on Fig. 2, which shows in some detail the hydrogeological setting for these springs.

So far, only the study has been made. Small diameter core boreholes will have to be sunk to determine the thickness of the aquifers below the present level of discharge, while experimental pumping to regulate discharge should be carried out during the summer-autumn of 1961 or of 1962.

1.1. *Geographical setting*

The Lilaia Group of Springs (at elevations of from 306.4 to 296.2 metres above sea-level) lie some 16 kilometres to the north-north-west of the summit (2425 metres) of the Parnassos mountain massif. Surface drainage is radial from this peak to the north and east, and the surface basin leading down to the springs extends back nearly to the summit of Mount Parnassos (fig. 2). The mountains are composed almost entirely of limestones with some dolomites, and the scenery is wild and precipitous. Basins of closed and completely karstic drainage surround the open basin, and these closed basins contribute substantially to infiltration and replenishment of the Lilaia spring waters. In addition, there are perched nappes in the overthrust Eastern Zone limestones-dolomites which are found to the east and west of the Lilaia Group basin, and also in a central area lying south of the springs. These overthrust limestones are underlain by impermeable flysch and do not contribute groundwater to the Lilaia Spring Group.

The Lilaia Spring Group discharges where the limestone aquifers meet the relatively impermeable alluvium of the Kifissos River plain; they are thus ideally situated for irrigation use. At present, some of their water is used for the irrigation of part of the area shown on figure 2; but most of their water flows unused into the main Kifissos River. In winter, this water then flows onto and across the Copais drained lake and from there into Paralimni and so to the sea. In summer, almost all the flow of the Kifissos River is utilized and summer losses to the sea are negligible. At one time, studies were carried out to see if the waters of these springs could be collected and piped to Athens for the domestic water supply of the capital of Greece;

thanks to these studies, detailed information is available as to the yield of the springs. A little water is pumped from Lower Agoriani spring for the domestic supplies of the village of Lilaia, formerly called Kato Agoriani.

As shown in figure 3, the Lilaia Group consists of five main springs as well as some seepages and points where on occasion there is a temporary winter discharge. However, the five main springs must account for some 99% of the total discharge, and the minor seepages may be disregarded. Table 1 is given here, to indicate the relative importance of Aghia Eleousa, Avissos, Gatsinos, Lower Agoriani and Mariolata which combine to yield an average of 68,550,000 cubic metres a year from the Lilaia Spring Group.

TABLE 1

Basic hydrological data on the five spring areas comprising the Lilaia Spring Group. Exhaustion Coefficients (z) and Residual Volumes have been calculated in all cases under "Neutral Conditions" assumed to exist between mid-April and mid-September.

Type of Data	Aghia Eleousa	Avissos + Gatsinos	Lower Agoriani	Mariolata	Lilaia group Totals
Annual yield, m^3	29,982,000	10,727,000	18,104,00	3,737,000	68,550,000
Average yield lit/sec.	950	340	575	310	2,175
Elevation (m)	306.4	(301.5) (296.6)	296.2	298.4	—
Exhaustion coeff. (z)	0.0116	0.00983	0.00523	0.01212	—
Residual volume	13,738,000	12,442,000	13,824,000	3,802,000	43,806,000
R. V. as % annual yield	46%	116%	76%	39%	64%
Average monthly yields, litres/second					
September	**246**	**89**	**263**	**67**	**665**
October	506	184	339	105	1,134
November	611	189	383	175	1,358
December	1260	494	686	365	2,805
January	1295	**654**	776	505	3,230
February	1484	648	**928**	**588**	3,648
March	1658	623	882	578	3,741
April	**1842**	546	836	532	**3,756**
May	1107	242	619	327	2,295
June	645	187	474	242	1,548
July	473	146	399	151	1,169
August	314	98	327	90	829

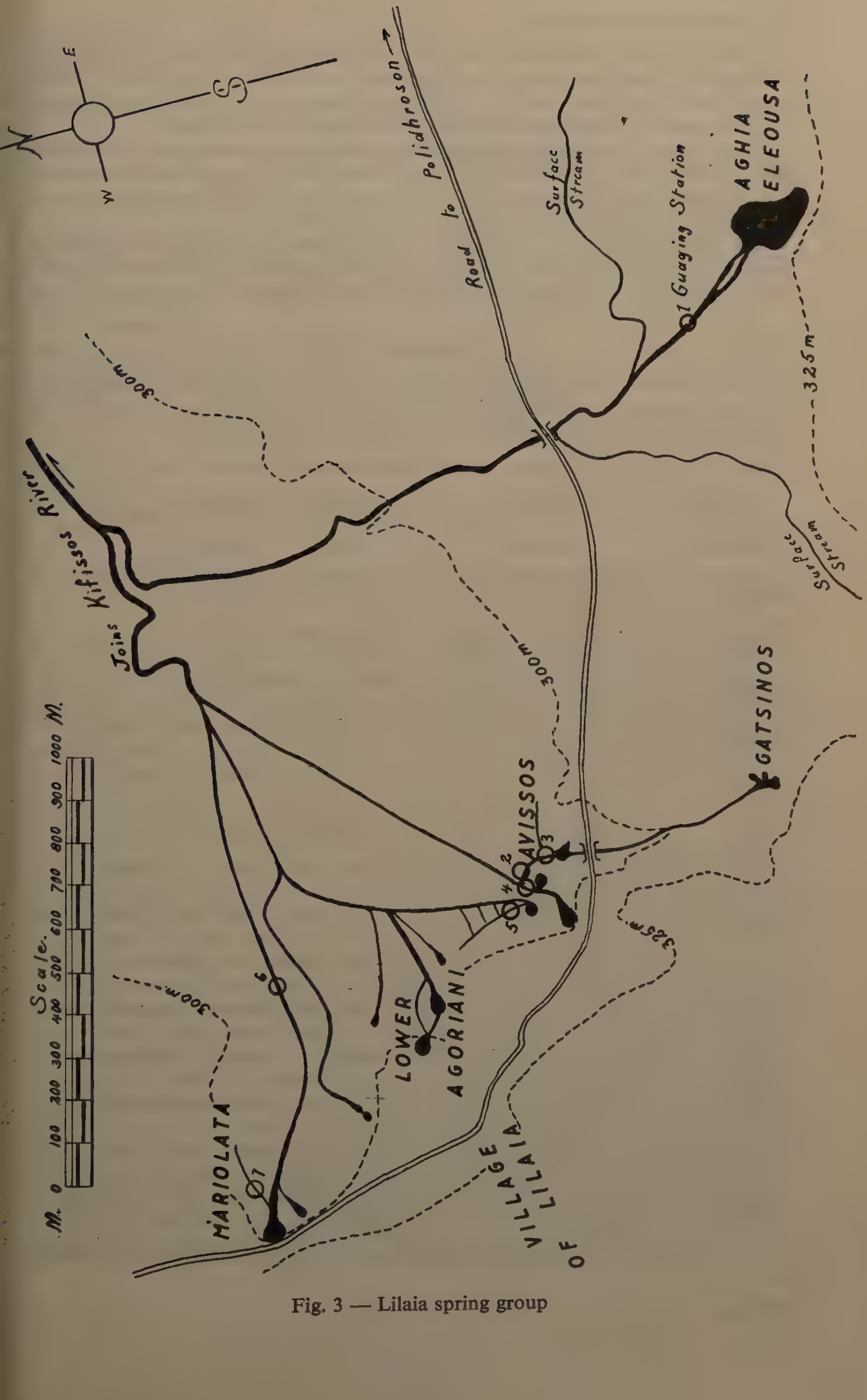


Fig. 3 — Lilaia spring group

1.2. *Climate and precipitation*

The region is one of comparative heavy rainfall, which is found to average just 1,400 mm for the groundwater basin draining towards the Lilaia Spring Group But as may be seen from Table 2, 74% of the precipitation occurs in the winter months from October to March inclusive, reaching a maximum in December.

The climate is typically Mediterranean, with high temperatures in summer, particularly in July-August, and with a cold winter, when much of the precipitation falls as snow. This is particularly so far all areas above 1400 metres elevation, and snow lingers into June on the northern face of Parnassos.

A new precipitation map has been calculated for the whole of the Parnassos-Ghiona, and will be described briefly in another communication (Burdon and Papakis) to be presented to this meeting. The isohyets for the basins contributing recharge

TABLE 2

Monthly distribution of precipitation (in mm) at three guaging stations situated near the Lilaia spring group. It will be seen that 26% of the average annual precipitation falls in the 'dry' six months of April to September inclusive.

Station	Gravia		Souvalas	Agorianis	Average for area
Elevation	400 metres		700 m	840 m	
Period	1934-40	1955-59	1934-40	1934-40	—
Annual	1143	1108	1306	1286	1210
January	147	154	173	159	158
February	117	99	154	130	125
March	118	141	126	120	126
April	88	79	90	97	88
May	82	20	88	88	70
June	76	52	74	93	74
July	9	23	26	28	21
August	10	12	10	10	11
September	29	98	32	39	50
October	119	183	138	123	141
November	110	158	129	117	128
December	238	89	266	280	218

to the Lilaia Spring Group are shown on figure 2; they have been omitted over the areas of perched watersheds, to emphasize the fact that these areas do not contribute groundwater to the Lilaia Spring Group.

1.3. *Selection of Aghia Eleousa Spring for Development*

For numerous technical and practical reasons, the Aghia Eleousa spring has been selected for experimental control of discharge.

Aghia Eleousa has the largest discharge of any of the springs of the Lilaia Spring Group. It has the highest elevation (306.4 metres), and so a drawdown here of up to 5 metres should have minimum effect on the other springs. The hydrogeological setting is clearer than for Avissos, Gatsinos or Lower Agoriani, which issue from alluvium or from under consolidated talus; Aghia Eleousa issues from solid limestone, though some more local detailed geological mapping is still necessary. There is a good guaging station, below which the pumped discharge can issue from the pipeline, so that pumped and free-flow yields can be measured separately. The limestone plateau may afford a good foundation for the pumping installation.

There is a good all-weather access road almost right to the spring. The water is not used for domestic supplies, and if dried-up in September, October, November and December (see fig. 6), nobody will suffer. There are archaeological remains (Aghia Eleousa is within the classical city of Lilaia), but they will not be affected by the investigation; ancient objects lost in the spring might even be recovered.

2. HYDROGEOLOGY OF THE GROUNDWATER BASIN FEEDING THE LILAIA SPRING GROUP

A determination of the exact limits of the basin which feeds groundwater to the Lilaia Spring Group has proved one of the most difficult tasks in this investigation. For the present, it is taken as 95 square kilometres, comprising the 12 sub-units designated *A* to *M* in Table 3 and on Fig. 2. The reasons for the boundaries chosen will be given in this section of the paper; but it is clear that they would benefit by some experimental data, possibly by the use of tracers introduced into some of the katavothres in say sub-areas *E*, *H* or *L*.

2.1. *Geology, Lithology, Tectonics and Structure*

The region has been mapped on the 1:50,000 scale by the Institute for Geology and Subsurface Research, and the Amphissa Sheet (published in 1960) and those for Amphiklia and South Parnassos reveal the complexity of the geology of Mount Parnassos. The region falls within the limits of the Alpine tectonic belt, here expressed more by thrusting and faulting than by folding; metamorphism is absent.

The region is composed of a great thickness of autoctonous to semi-autoctonous limestones and dolomites (the Parnassos-Ghiona Zone), ranging in age from Triassic to Palaeocene and overlain conformably by flysch which extends from the Palaeocene to the Oligocene; see Fig. 4. It is presumed that the base of the Triassic dolomite rests on the Paleozoic basement, but this is nowhere exposed. The main Jurassic consists essentially of limestones, with a total thickness of the order of 450 metres. It terminates at an unconformity, on which bauxite of the lower horizon has been deposited. The lower bauxite is overlain by limestones, commencing at the Tithonian and ending in the Cenomanian. Here again there is an unconformity, marked by the deposition of the bauxite of the upper horizon. This upper bauxite is overlain by Upper Creteceous and Palaeocene limestones which, as already noted, pass conformably upwards into the flysch.

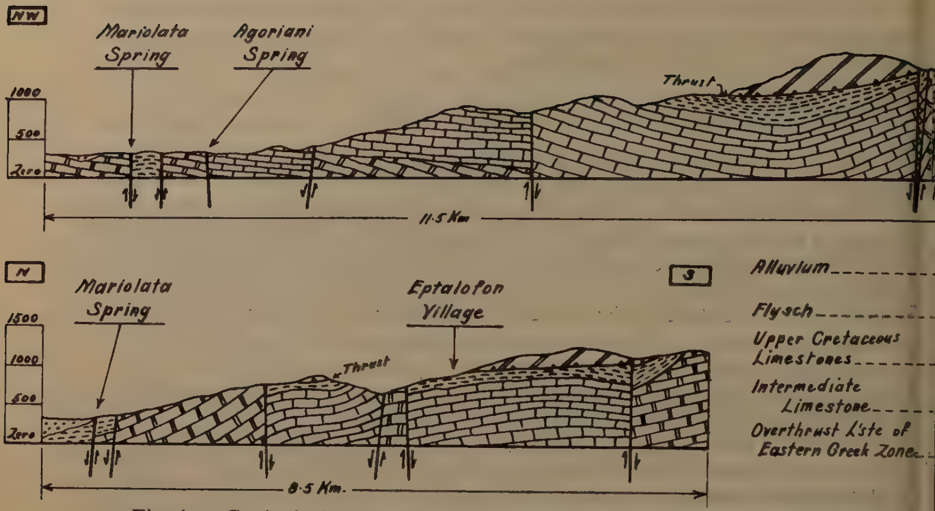


Fig. 4 — Geological sections of the Lilaia spring group ground water basin

In the region under study here, the limestones of the Parnassos-Ghiona zone have been thrust southwards and have over-ridden themselves along a series of east-west thrust zones, of which the most northernly runs through the Delphi-Valley. Thrusting has taken place on the flysch, a relatively plastic formation which has flowed and yielded to lubricating the movement of the hard limestones and dolomites. There has been drag-folding along the thrust planes, and the flysch outcrop of the Delphi-Arakova valley forms a barrier to the southwards movement of the groundwater in the limestone aquifers of the Parnassos mountain massif.

The great thickness of the sediments forming the Parnassos Massif suggests duplication of strata by thrusting. Such thrusting would most probably occur on and over the flysch beds. Hence the general limestone sequences of Parnassos may be interrupted by flysch beds; such flysch beds would occur in zones of thrusting and are more likely to be lenticular and shattered rather than continuous and uniform. So it is considered that they do not form extensive impermeable barriers to groundwater movement at depth in the Parnassos Massif.

In addition to such southwards thrusting of the autoctonous series, there has been a major invasion of the region by limestones-dolomites of the Eastern Greek Zone. They also moved on the plastic layer of the flysch, and at one time must have covered most of the northern flanks of Parnassos. Erosion has removed most of the invaders from the East, and they are now represented in our area by three large areas. On the east, there is the Anokalivia-AnoPolidhroson Triassic dolomite block; on the south there is the Eptalofon Triassic dolomite block; while on the west, the Gravia-Varyianni block is also of the Eastern Zone but is a Cretaceous limestone with some Eastern Zone flysch. The relationships of these blocks to the Parnassos-Ghiona Zone series are indicated on the sections of Fig. 4.

To the south of the Eptalofon Eastern Zone overthrust block, there is a smaller block of Parnassos-Ghiona Cretaceous limestone which appears to be overthrust into the flysch which outcrops all around it. This limestone block also appears to be isolated from the underlying limestore by the flsych and gives rise to a big winter spring flowing onto the Kalivia alluvium. Hence, this limestone area is also regarded as supporting a perched nappe of groundwater and will be called the Kalivia overthrust block.

To avoid confusion, faults have had to be omitted from Fig. 2, though they are shown on the geological sections of Fig. 4. There are numerous vertical faults in the area between Parnassos Summit, Kalivia, Eptalofon and Ano-Polidhroson, and all the major ones strike south-east by north-west. They are large faults, many extending unbroken for up to 10 kilometers; and they all seem to point to the Lilaia Spring area. They affect the direction of groundwater movement as clearly as they determine the location and direction of the surface drainage.

The talus cover of the slopes and the piedmont deposits, as well as the Quaternary and Recent alluvium of the Kifissos plain and the Kalivia closed basin, present few geological difficulties, though they are of great hydrogeological importance.

2.2. *Aquifers and Aquicludes*

It is clear that the limestones of the Parnassos-Ghiona Zone are the aquifers feeding the Lilaia Spring Group; to emphasize their unity, they have all been left unhatchured on Fig. 2. They have been fractured by slight folding, by thrusting and by faulting; they have been subjected to heavy precipitation; and there is no doubt at all that they have been karstified intensively by the movement of groundwater through them.

In addition to this current karstification, there are strong reasons for suspecting the development of karst at two earlier geological periods. Without going into theories as to the method of formation and emplacement of the bauxite, it must be accepted that the bauxite occurs over karstic erosion surfaces (as in Papastamatiou, 1955). In fact, the presence of the bauxite attests to the prevalence of karst development in the pre-Tithonian Jurassic and the pre-Turonian Cretaceous. Whether or not the bauxite occurs at the base-level of karst development or whether there was prior karstic weathering below the bauxite horizons is still not certain, though the investigation is continuing. The general opinion is, however, that traces of two earlier karstifications of the limestones of the Parnassos-Ghiona region still exist.

The flysch is the main aquiclude of the region. It consists of red or grey argillaceous material, locally coarser and harder, and becoming more pebbly and gravelly towards its top. Pebbles of serpentine are common, and they give a high magnesium content to the groundwater which comes in contact with them. Though the weathered flysch becomes slightly permeable and gives rise to numerous small springs (of the order of 2 to 4 cubic metres per hour), while its harder beds may joint and also give rise to springs of a similar magnitude, by and large, and without exception, the flysch is a definite and firm aquiclude. This is best attested by the numerous springs which are found around the edges of the four overthrust limestone blocks; these springs issue at the base of the limestones-dolomites, at their contact with the underlying flysch.

The alluvium of the Kifissos River plain is of major hydrogeological importance. To a limited extent, it has been tested by wells and boreholes (including four drilled by the British Army in 1914-18) and found to yield good quantities of groundwater. Particularly, towards the feet of the encircling mountains, the alluvium should be coarse and a good aquifer. Nevertheless, the Lilaia and other springs are forced out at the contact of the limestones with the alluvium. This may be due to the fact that the alluvium aquifers are already fully charged with water, and the water must issue; it is probable that the permeability of the alluvium is less than that of the karst limestone, and outflow is easier than displacement for the groundwater.

The talus is a good aquifer, and where it overlies flysch, or other impermeable beds, it gives rise to springs; unless fed from limestones, these are small and dry-up in summer, for the area of outcrop of the talus available for infiltration is almost always small. Where the talus overlies limestone, its waters are lost into the underlying sponge of karst.

2.3. *Movement of Groundwater and Limits of the Groundwater Basin*

In as far as it can be deduced for the 95 square kilometres feeding groundwater to the Lilaia Spring Group, the direction of movement is shown by arrows on Fig. 2. The arrows are confined to those areas which are considered to supply groundwater to the Lilaia Spring Group.

As already explained, the limestone of the four overthrust blocks support perched nappes, and do not feed the Lilaia Spring Group. The Anokalivia AnoPolidhroson block feeds large springs at AnoPolidhroson, and the Eptalofon block feeds a large spring just south of the village; these two spring groups have an average annual discharge of 14,450,000 cubic metres. Some details are given in Table 6, but lie somewhat outside the scope of the present study. It is possible that some water does reach the Parnassos-Ghiona limestone aquifers from these perched blocks, either through windows where there is no flysch subterranean barrier, or through faults which provide a downwards passage through the flysch layer. But the presence of the large springs suggested that the perched nappe is held without any real communication with the deeper limestones. The surface runoff of these springs and from the flysch outcrops may also contribute to the groundwater of the Parnassos-Ghiona aquifers. It is extremely difficult to calculate such an addition, and is not warranted when so many other factors are uncertain or unknown.

Accordingly, the eastern limit of the groundwater basin feeding the Lilaia Spring Group is readily fixed at the edge of the Anokalivia-AnoPolidhroson Eastern Zone overthrust block, while the western limit lies at the edge of the Gravia-Varyianni overthrust block. It will be also noted how the flysch at the edges of these two blocks is brought down into contact with the alluvium of the plain, forming sidewalls to the underground limestone conduit directing the waters towards the Lilaia gap.

Within the basin itself, the overthrust Eptalofon and Kalivia limestones and their flysch surround are also excluded from contributing to the Lilaia Spring Group. The Kalivia block discharges as a winter spring onto the Kalivia alluvium, which is impermeable. The water forms a winter lake from which some is evaporated, some stored in the soil, some regains the limestone through a katavothre, while some is led via a canal, tunnel and waterfall to irrigate Arachova and Delphi lands on the flysch to the south. Thus, some does regain the Parnassos-Ghiona limestone aquifers, but the amount is uncertain, and the alluvium of Kalivia has been excluded as a contributor to the flow of the Lilaia Spring Group.

We now turn to those areas which are considered to feed the Lilaia Spring Group, and they are listed in Table 3. There are 12 such sub-areas, and they have been lettered and listed separately, so as to show how the areas and volume of annual precipitation increases as each additional area is included. The open drainage areas, *A* and *B* can be accepted without question; so can most of the small closed basins carrying letters *C* to *J*. This brings the total volume of annual precipitation to 77.4 million cubic metres, and with a guaged discharge from the Lilaia Spring Group of 68.6 million cubic metres (Table 1), it is clear that more areas must be added. The major Kalivia basin of closed drainage must, on structural-lithological grounds, drain underground to the north; and it has been subdivided into three sub-areas, lettered *K*, *L* and *M*, so that the effect of each addition can be seen.

In the end, we arrive at a supply basin covering 95.0 square kilometres, with an average annual volume of precipitation amounting to 133 million cubic metres of water. Ignoring subsurface transfer from the limestones to the alluvium of the Kifissos

TABLE 3

Area of 12 sub-basins, together with volume of annual precipitation, which cover 95.0 square kilometres with a total annual precipitation of 133 million cubic metres and which form the total infiltration basin feeding groundwater to the Lilaia Spring Group

Basin			Average Precipitation	Amount of water	
No.	Area	Prog. Total		Per Basin	Progressive
A	39.8	—	1,260	51.0	—
B	5.6	45.4	1,380	7.7	58.7
C	2.7	48.1	1,480	4.0	62.7
D	2.7	50.8	1,450	3.9	66.6
E	3.6	54.4	1,480	5.3	71.9
F	1.0	55.4	1,440	1.4	73.3
G	0.2	55.6	1,440	0.3	73.6
H	2.3	57.9	1,450	3.3	76.9
J	0.3	58.2	1,520	0.5	77.4
K	9.6	67.8	1,550	14.9	92.3
L	3.0	70.8	1,450	4.4	96.7
M	24.2	95.0	1,500	36.3	133.0
Totals	95.0	—	1,400	133.0	—

Plain, the amount infiltrating must be 68.6 million cubic metres, or 51.6% of the total precipitation.

Considering the amount of snow, the low evapo-transpiration losses from winter rain, the closed drainage of much of the area and the extensive development of karst, the infiltration of only 51.6% of the annual precipitation must be considered a little low. From the open basin, there is a strong surface runoff after heavy rain, but unfortunately there are no guagings or even reliable estimates of the amount. For the present, the minimum figure of 51.6% infiltration will have to be accepted.

From the foregoing considerations, the arrows showing movement of groundwater have been drawn-in on Fig. 2, but with a certain amount of reserve for the southern edge of the Kalivia closed basin.

2.4. *Hydrochemistry of the Lilaia Spring Group*

The hydrochemistry of the Parnassos-Ghiona aquifers is described in another paper (Burdon and Dounas) to be presented to this meeting, and so only the inferences drawn from this work need to be presented here. However, for easy reference, six chemical analyses are reproduced in Table 4.

TABLE 4

Results of chemical analyses made on the three main springs of the Lilaia Spring Group, for comparison with waters from the perched nappes at Ano-Polidhrosos and Eptalofon

Location	Lilaia Spring Group			Ano-Polidhrosos		Eptalofon
Name of Spring	Ag. Eleousa	Agoriani	Mariolata	Ay. Varvara	Kyria	Manna
Sample Number	139	14	71	69	70	151
Ca (meq)	2.29	2.40	1.76	1.10	0.80	2.29
Mg ”	0.50	0.08	0.04	2.00	3.49	0.20
Na + K ”	0.07	1.27	0.15	0.09	0.09	0.08
HCO_3 ”	2.46	3.96	1.76	3.13	3.84	3.38
SO_4 ”	0.20	0.22	0.06	0.24	0.36	Nil
NO_3 ”	0.01	0.05	0.08	Nil	Nil	Tr.
Cl ”	0.15	0.25	0.25	0.20	0.25	0.15
T.S.S. in ppm	219	351	164	252	321	274

The two waters (Nos. 69 and 70) from the Ano-Polidhrosos overthrust Eastern Zone Triassic dolomite are readily distinguished and separated by their high magnesium: calcium ratio; this is due in part to a dolomitic aquifer and in part to magnesium dissolved from the serpentine in the flysch. The hydrochemical data thus supports the other hydrogeological evidence that this nappe is separate from that held in the main Parnassos-Ghiona limestone aquifers.

The water from the main spring, Manna, draining the Eptalofon overthrust Eastern Zone dolomite-limestone is not distinguished by a high magnesium-calcium ratio. In part, this is due to the absence of coarse serpentine-bearing flysch in the vicinity of the discharge point, but it also suggests differences in the calcite-dolomite ratio of the limestones-dolomites of the two overthrust blocks.

Within the Lilaia Spring Group itself, it will be noted that the two springs which issue direct from limestone, Aghia Eleousa and Mariolata, are the least mineralized and rather resemble each other; magnesium is more prominent in Aghia Eleousa waters than in those from Mariolata. The Lower Agoriani water is surprisingly high in sodium and is more mineralised. It passes through talus beneath the village, and some organic contamination might be expected. The low nitrate disproves this but the presence of the sodium has not yet been explained. Additional samples of all the Lilaia Spring Group individual springs have been taken on the same day, and sent for chemical analysis; results have not yet come to hand.

3. HYDROLOGY OF THE LILAIA SPRING GROUP

Data on the guaged yield of each of the springs has been obtained from the records of the Athenian Water Supply Company, thanks to the courtesy of its Director,

TABLE 5

Average monthly yields, in cubic metres per month for the five springs of the Lilaia Group. Averages are based on 14 years of observation, 1933/34 to *1941/42, 1946/47 and 1949/50* to *1952/53.*

Month	Aghia Eleousa	Avissos + Gatsinos	Lower Agoriani	Mariolata	Total Lilaia Group
September	648,000	231,000	682,000	174,000	1,735,000
October	1,355,000	493,000	908,000	281,000	3,037,000
November	1,584,000	490,000	993,000	454,000	3,521,000
December	3,375,000	1,323,000	1,837,000	978,000	7,513,000
January	3,469,000	1,752,000	2,078,000	1,353,000	8,652,000
February	3,591,000	1,568,000	2,245,000	1,422,000	8,826,000
March	4,441,000	1,669,000	2,362,000	1,548,000	10,020,000
April	4,774,000	1,415,000	2,167,000	1,379,000	9,735,000
May	2,965,000	648,000	1,658,000	876,000	6,147,000
June	1,672,000	485,000	1,229,000	627,000	4,013,000
July	1,267,000	391,000	1,069,000	404,000	3,131,000
August	841,000	262,000	876,000	241,000	2,220,000
Total	29,982,000	10,727,000	18,104,000	9,737,000	68,550,000
Lit/Sec.	950	340	575	310	2175

Mr. A. Georgalas. They cover the 9 continuous years 1933-34 to 1941/42, the year 1946/47, and the four continuous years 1949/50 to 1952/53. The precipitation records are, as shown in Table 2, mainly for the seven years from 1934 to 1940, plus data on the 1955 to 1959 period at the Gravia station.

3.1. *Yields of the Lilaia Spring Group*

The average monthly yields for the 14-year period are given in Table 1, expressed in litres per second, and separately for the Aghia Eleousa, Avissos plus Gatsinos, Lower Agoriani and Mariolata, as well as for the combination of these five springs

TABLE 6

Total annual yield in cubic metres of the Lilaia Spring Group and the High-Leve Spring Group for 14 years. The combined total averages 83 million cubic metres per year, equivalent to 2,365 litres per second. For comparative purposes, the average annual rainfall (based on the Gravia, Eptalofon and Ano-Polidhroson stations) is given for the years for which it is available.

Meteorological year September-August	Lilaia Spring Group yield in m³	High-Level Spring Group yield in m³	Precipitation Average of 3 stations
1933-34	66,617,000	9,704,000	1,021 mm
1934-35	63,507,000	9,704,000	1,126 cm
1935-36	42,540,000	8,369,000	1,097 mm
1936-37	42,089,000	13,075,000	1,106 mm
1937-38	82,506,000	29,539,000	1,372 mm
1938-39	83,206,000	17,982,000	1,694 mm
1939-40	87,485,000	19,938,000	1,256 mm
1940-41	72,904,000	11,985,000	
1941-42	78,317,000	9,933,000	
1946-47	*89,559,000*	13,948,000	
1949-50	62,908,000	14,136,000	
1950-51	50,818,000	11,850,000	
1951-52	73,560,000	18,778,000	
1952-53	63,680,000	13,333,000	
14 year average	68,550,000	14,450,000	

which form the Lilaia Spring Group. These average monthly yields have also been plotted on Fig. 5, on which average monthly precipitation is also plotted in a form suitable for comparison of yield with precipitation.

The data, in cubic metres per month, is also presented in Table 5; this data for Aghia Eleousa has been plotted in Fig. 6, so as to see the effect of the proposed controlled development and extraction of the water of that spring.

It will be noted that for all the springs, minimum discharge rate is reached in September, while the maximum rate occurs in April for Aghia Eleousa, in January for Avissos + Gatsinos, and in February for Lower Agoriani and Mariolata. The relative sizes of the different springs are shown, and the predominating position of Aghia Eleousa is clear.

There are strong fluctuations in yield from year to year, and this is shown in Table 6, which gives the total annual discharge of the Lilaia Group for the 14 years for which detailed records are available. Table 6 also shows the annual yield of the high-level springs draining two of the perched nappes, one around Ano-Polidhroson and the other south of Eptalofon. It will be noted that maxima and minima do not occur in the same year for the two groups; thus, the Lilaia Group had a maximum yield in 1946/47, in which year the High-Level Group had a discharge even below the 14-year average.

3.2. *Relationships between Precipitation, Rate of Underflow and Spring Yield*

For all the springs examined, there is a very close relationship between the average monthly rainfall and the average monthly spring discharge; this is shown clearly in Fig. 5, and also on Fig. 6. On Fig. 5, the precipitation data of Table 2 has been combined with the spring yield rates of Table 1; but the two figures do not cover the same periods of time, and while the springs have been associated with the rainfall station closest to each, still the average precipitation of Fig. 6 might be a more correct basis of comparison. In any case, the comparison must not be pushed too closely, but accepted only in a general manner.

The precipitation peak is generally in December, and this produces peak discharges first in the two smallest springs of Gatsinos and Avissos, then in the larger springs of Mariolata and Lower Agoriani, and finally, in April, in the greatest spring, that of Aghia Eleousa. Clearly, the larger the basin feeding any one spring, the longer it takes for the greater portion of the infiltrating precipitation to reach that spring. This fact is in agreement with the main hydrogeological system of these springs. We may say that there is a lag of from one to four months, depending on the distance of travel, before the peak precipitation is reflected in peak discharge. In the most general terms, this would indicate an horizontal rate of movement of 3 kilometres per month, or 100 metres per day, for groundwater flowing through the karst limestone aquifers.

The retardation due to the delay in melting of snow is disregarded, but if it has an appreciable effect, it would indicate a faster rate of travel of the groundwater through the aquifers than the 100 metres per day already estimated. Likewise, after heavy infiltration, the head causing flow is at its maximum; hence the rate of flow at such times will be at its maximum, and exceed the average flow rate for the aquifer. Since the infiltrating precipitation and/or snow-melt has to travel downwards as much as 2,000 metres from the peaks of Parnassos, allowance must also be made for the vertical component of movement in determining the actual effective rate at which the groundwater passes through the karst limestone aquifers; the Paleozoic basement may of course be reached above the 300 metre level in central Parnassos. But all in all, 100 metres per day of horizontal travel is a useful figure when dealing with the movement of groundwater in this karst limestone.

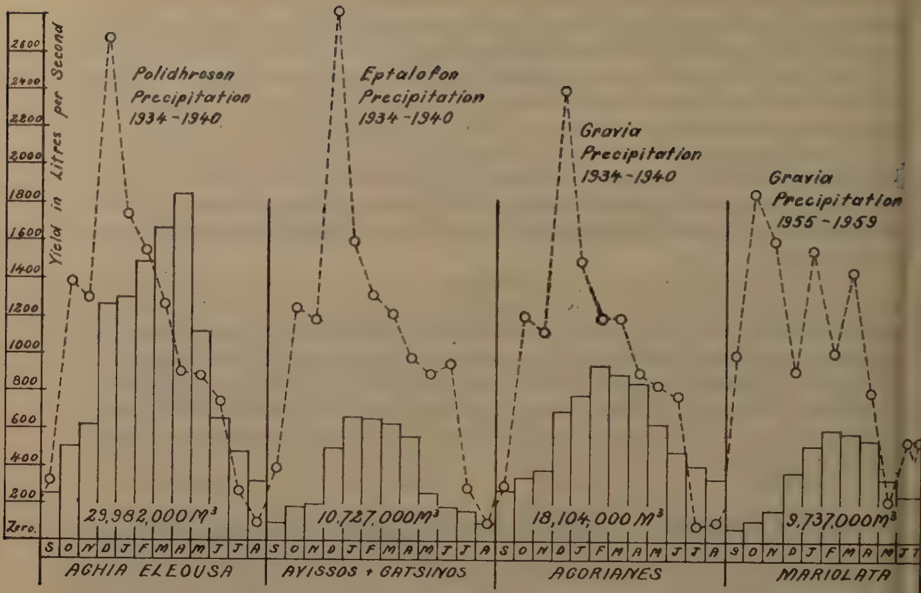


Fig. 5 — Lilaia spring group and drainage basin individual yields and precipitation

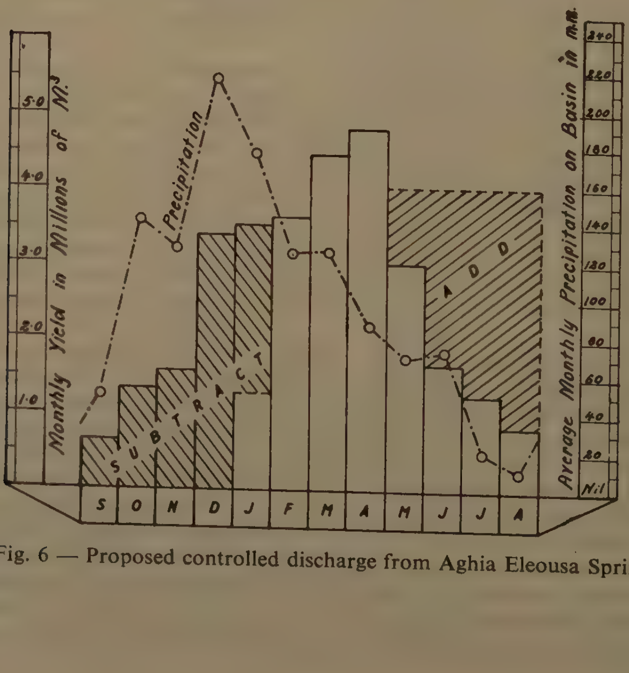


Fig. 6 — Proposed controlled discharge from Aghia Eleousa Spring

Minimum rainfall occurs in August, and minimum yield for all the springs of the Lilaia Group occurs in September. The increased precipitation of September is thus rapidly reflected by increased spring discharges in October. The effect of even small recharge is most noticeable when the springs have reached a low discharge rate.

Correlation between total annual precipitation and total spring discharge for any one meteorological year is surprisingly poor, as may be seen from Table 6. This is probably due to the fact that the three precipitation stations are situated at the lower portion of the catchment, while most of the precipitation occurs at the higher altitudes, far from the stations. In such mountainous country, variations of rainfall from one valley to the next are common; while such variations may average out over a long period of years, they invalidate inferences made as to total annual precipitation in any one year based on data from three low-altitude gauging stations.

There can be no doubt (see Section 3-3, following) that none of the aquifers feeding the springs contain a large reserve of water to be carried forward from one meteorological year to the next. Hence, the spring discharge of any one year must effectively represent the infiltration, and so the precipitation on its basin, for that same year. In such cases, and excluding abnormal years with changed groundwater drainage conditions, spring discharge can be a more accurate indicator of total precipitation on the basin than the precipitation figures from a few rain-guages.

3.3. *Rates of Exhaustion and Residual Volumes in Storage.*

Following the classical methods of Edmond Maillet (1905), the coefficient of exhaustion (z), and the volume of groundwater in storage in the aquifers have been calculated for the four spring areas of the Lilaia Spring Group. This method has been applied with considerable success in Lebanon and Syria, (Abd.-el-Al, 1952; Burdon and Safadi, 1961), but there the catchments are under «neutral conditions», that is, free of all sources of recharge, over at least five months of the year. In the Lilaia Spring Group groundwater basin, there is some precipitation every month, and snow-melt also contributes to the groundwater into June. In order to obtain comparative figures, and estimate as closely as possible how the springs function, it has been assumed that «neutral conditions» prevail for the 150 days from mid-April to mid-September. On this basis, the following calculations have been made.

Let

Q_a = Max. Spring yield (i.e. on 15 April) in m^3/sec.

Q_i = Min. spring yield (i.e. on 15 September) in m^3/sec.

t = Time in days which has elapsed from 15 April.

z = coefficient of exhaustion.

V_o = Volume in storage (m^3) on date on which Q_a occurred.

Then

$$Q_i = \frac{Q_a}{(1 + z.t)^2}$$

$$\text{and } V_o = \frac{Q_a}{z}$$

For Aghia Eleousa spring, Q_a equals 1.842 m_i/sec., and Q_i equals 0.246 m^3/sec., while the time interval between Q_a and Q_i is 150 days. Accordingly,

$$0.264 = \frac{1.842}{(1 + 150 \times z)^2}$$

and so, $z^2 + 0.013333 \times z - 0.0002883 = 0$
from which, the positive solution is $z = 0.0116$.

The storage in the aquifers on 15 April can then be readily calculated as 13,738,000 cubic metres of groundwater.

Similar calculations have been made for Avisos + Gatsinos, for Lower Agoriani and for Mariolata, and the resulting figures are given at the top of Table 1. They will now be discussed briefly.

The larger the Exhaustion Coefficient, *z*, the smaller the Residual Volume of groundwater which is in storage on the day on which «neutral» conditions commenced. Thus, for Aghia Eleousa, in an average year, there are only some 13.7 million cubic metres of groundwater in the aquifer feeding this spring on 15th April. If there were no recharge after that date, and if the discharge rate did not change from average (a completely hypothetical occurrence), then by end-August, Aghia Eleousa would cease to flow and not a drop of groundwater would remain in the aquifers which normally feed it.

For Avissos + Gatsinos, the Residual Volume on 15 April is 116% of the annual discharge, so without recharge, this spring could continue to discharge normally for just over a year. For Lower Agoriani, the relative percentage is as high as 76%, but for Mariolata, it falls to 39%, and for the Lilaia Spring Group as a whole, it is estimated at 64%. Hence, for all these springs, there is no great reserve of groundwater in the limestone aquifers which feed them, and which could carry over from one hydrological year to the next, smoothing out differences in annual precipitation into a more regular discharge. So, a meteorological year of high precipitation must produce a year of high spring discharge; and a year of low precipitation must produce a year of low spring discharge.

4. DEVELOPMENT OF THE AGHIA ELEOUSA SPRING

4.1. *Object of Development*

The object of the development is to determine how much additional water can be obtained from the Aghia Eleousa spring during the irrigation months of May, June, July and August, and thereby reduce the unused flow of September, October,

TABLE 7

Planned changes in the irrigation-season flow of Aghia Eleousa. a member of the Lilaia Spring Group. It is anticipated that once pumping starts, natural flow will cease; so the full 16 million cubic metres of water will have to be pumped.

Month	Natural yield m^3	Planned pumped increase, m^3	Total planned yield, m^3
May	2,965,000	1,035,000	4,000,000
June	1,672,000	2,328,000	4,000,000
July	1,267,000	2,733,000	4,000,000
August	841,000	3,159,000	4,000,000
4 months	6,745,000	9,255,000	16,000,000

November, December and part-January to nil or negligible amounts. A preliminary plan for such a change in the temporal distribution of the yield from the spring is shown in Fig. 6, and may be summarised as in Table 7.

It is also clear that of the 16 million cubic metres to be extracted during these four months, only 9.3 million will become available for new irrigation on the Kifissos Plain north of the spring; the balance will have to be replaced in the river, to supply traditional water rights further down the river.

4.2. *Geological Investigations*

From the present state of geological mapping, it appears that Aghia Eleousa spring is ideal for development. It occurs at the junction of the flysch with the limestone, and this prevents any further migration of the groundwater to the eastwards. This flysch/limestone contact appears to be a normal, concordant one; but some faulting is possible. On surface, the contact to the north is between the limestone and the alluvium; in depth, there are reasons for hoping that more flysch underlies the alluvium, and seals all deeper subsurface transfer of groundwater from the limestone into the alluvium. While such an additional barrier is not essential to the pumping scheme, it would help by further delimiting the zone through which the groundwater could move; and should the flysch barrier be located at shallow depth, and be found to extend beneath an extensive area, then the possibility of building a subsurface-surface dam to raise the spring level in winter and so reduce wasted winter flow would have to be taken into consideration.

On the east, the limestone-alluvium contact continues at surface and there are no lithological obstacles to a movement of the groundwater in this direction. The lack of a barrier here does not affect the pumping scheme, but might prove detrimental to any plan to raise the level of the spring in winter. Beneath the spring itself, or a few metres to the south, the limestones extend downwards to an indefinite depth, as far as is known at present; such a downwards extension is essential to the pumping scheme, and must be ascertained beyond the shadow of a doubt. Trial boreholes will go to depths of about 50 m.

Some additional, very detailed geological mapping is necessary, and this will be supplemented by core-drilling, to obtain more geological data as well as hydrogeological data regarding the existence and extent of the karstic limestone groundwater reservoir from which the additional groundwater will be pumped.

4.2. *Investigation into Existence and Extent of the Deeper Groundwater Reservoir*

The success of the proposed control of yield depends on the existence of a groundwater reservoir in the karstic limestones at a level below which its stored water could flow by gravity to the Aghia Eleousa spring at 306 metres elevation. A very diagramatic presentation of this problem of groundwater reservoir engineering is presented in Fig. 7, showing the position in the second-half of April of an average year.

That the karstification of the limestones of this region of Parnassos has extended below the 306 metre elevation level of Aghia Eleousa seems highly probable. In part, such karstification may have occurred in the geological past (the pre-Tithonian Jurassic and the pre-Turonian Cretaceous of Section 2-2), and in part during the Pleistocene and Recent, before the accumulation of alluvium had raised the discharge threshold to its present level; the Pleistocene lowerings of Mediterranean sea-levels may have had an effect inland in addition to the well-known coastal effects. Accordingly, it is accepted that the karstification of the limestone extends below Aghia Eleousa, and a porosity of 2% is assigned to the limestone en masse. This may be a little high,

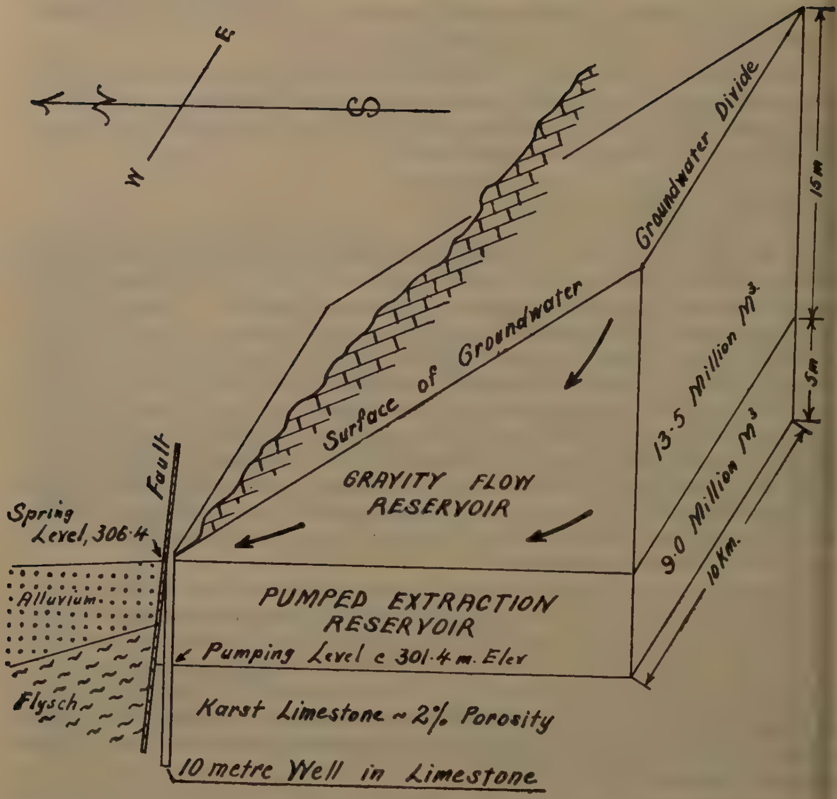


Fig. 7 — Diagramatic presentation of gravity flow and pumped extraction groundwater reservoirs supplying aghia elousa.

but is not unreasonable; thus Walker (1956) reports a storage coefficient of 0.5% for a limestone of Mississipian age in Kentucky.

Nine million cubic metres of groundwater could accordingly be stored in a limestone extending over 90 square kilometres of area, with a thickness of 5 metres, and with a 2% porosity. This forms the "Pumped Extraction Reservoir" of Fig. 7.

It has already been calculated (Section 3-3) that in mid-April of an average year, there are some 13.5 million cubic metres of groundwater stored in the limestone reservoirs actively feeding under gravity flow to the Aghia Eleousa spring. Again assuming a 2% porosity, and a basin 90 square kilometres in extent (as against the 95 square kilometres of Table 3), these 13.5 million cubic metres could be stored in wedge-shaped form, with nil thickness on the north (Aghia Eleousa discharge point-zone) and 15 metres high on the south. Such groundwater would flow under gravity to Aghia Eleousa, and this body is called the "Gravity Flow Reservoir" of Fig. 7.

This simplified scheme ignores many facts. Thus, it is made to appear that there is an impermeable horizontal barrier between the Gravity Flow Reservoir and the

Pumped Extraction Reservoir. In fact, under natural conditions, much of the water issuing from Aghia Eleousa will move through the Pumped Extraction Reservoir volume, and rise-up under differential pressure heads to flow out at the spring. This movement will have assisted in the karstification of the limestones below the 306 metre elevation of Aghia Eleousa. Again, full extraction is postulated; even in the most highly permeable aquifer, some slight gradient will have to remain to cause the water to move to the point of gravity or pumped outflow. It is assumed that the whole of Parnassos is uniform karst limestone, with no impermeable basement. The change in the area of the reservoir due to pumping is ignored. Again, all the 13.5 million cubic metres in the «Gravity Flow Reservoir» may have to be extracted before any water can be drawn from the «Pumped Extraction Reservoir».

Despite these, and other limitations, it is thought that Fig. 7 does clarify many problems regarding the existence and the extent of the groundwater reservoirs which will be exploited under the proposed development of Aghia Eleousa.

4.3. *Trial of Controlled Development by Pumping*

Provided the additional geological investigations and the core-drilling confirm the present favourable set of eircumstances, then it will be necessary to carry out a trial of the planned controlled development by test-pumping from the Aghia Eleousa spring.

Published information on such control of a karst spring is very sparse. In Syria, Ain Senn was controlled by raising the outflow level, while Ain Figeh had its outflow level dropped in the course of development; some notes on these will be found at the end of Ayoub's 1952 UNESCO paper. There is a report that some experimental pumping was carried out on a talus-piedmont to the north of Teheran, but nothing is known of the results. It seems improbable that such development has not been tried, but certainly the results have not been widely published.

Within Greece itself, pumping from wells sunk on limestone springs has already commenced. Such control has given good results at a spring belonging to Moulki village near Aliartos and also in the lands of Ipsilanti village. Unfortunately, no data or gaugings are available on pre-pumping yields nor on the effects of pumping.

The test-pumping on Aghia Eleousa might be made from the existing pool below the spring, permitting a drawdown of about one metre, that is lowering the discharge level from the natural 306.4 metres to 305.4 metres. Probably a greater drawdown will be required even for effective testing, and a well, located on the limestone above and just south of the main point of issue, will have to be sunk for some 8 to 10 metres. Due to the large discharge, an open well may not be feasible, and a borehole may be necessary. The lift will have to be kept small, so that a centrifugal pump, with a suction intake can be employed. Further details will have to depend on the size, number and operating characteristics of such high-yielding, low-lift pumps as may be available for this operation.

The effect of the test-pumping on the other springs of the group will have to be determined. While they all have much lower outflow levels (Gatsinos, the next highest is at 301.5 metres; see Table 1), some of their underflow may be directed to Aghia Eleousa when its effective discharge level is lowered by some 4 to 5 metres. Nothing is gained by increasing the Aghia Eleousa yield by pumping and thereby decreasing the free flow of the other springs by a similar amount. Hence the effect of the pumping can only be measured by careful guaging of the yield, not only of Aghia Eleousa under test, but also of the other springs of the Lilaia Group. The levels will also have to be observed. It would facilitate such work if discharge rating curves could be constructed for all the springs of the Group; then only levels would have to be read, while discharges could be read from the discharge curves.

At the conclusion of the test-pumping, it is hoped that the Aghia Eleousa spring will have no natural discharge for some time; as recharge replenishes the over-depleted aquifers, the spring will commence to flow again. The time-lag, and the new rates of flow, will have to be observed and measured with care; they will give much information on the characteristics of the groundwater reservoir feeding this major karst spring. If the trial results are satisfactory, rates of pumped extraction can be increased in the permanent plant, so that free flow of the spring would not, in an average year, recommence till mid-March, or other suitable date.

4.4. *Agricultural, Social and Economic Factors*

On the Kifissos plain, there is a strong demand for summer irrigation water, and numerous wells and boreholes have been sunk to obtain supplementary groundwater for irrigation, especially for cotton. Due to existing rights on surface waters, pumping from the river and the spring-fed streams is not permitted. The exact location of the lands which might be irrigated with the planned 9.3 million cubic metres of irrigation water has not been determined; but such a survey will be relatively simple once the feasibility of getting such additional water has been proved.

Due to the outwash talus fan to the north of Aghia Eleousa, there are some marshy lands in this area, which grow reeds. It has proved difficult to fully drain these lands in the past. But if the spring-level is lowered by some 5 metres during most of the growing season, such lands (which at present provide grazing) will become suitable for crop-growing. On the other hand, the lowering of the water-table, and possible cessation of flow from September to December, is unlikely to prove inamicable to the trees of the area.

The decrease in the flow of the spring during early winter will be masked by the runoff from rainfall. However, if such spring development were to be extended to all the springs of the group, and other karst springs in the Kifissos River basin, less water would be available further downstream. At the present stage of the investigation, such basin-wide considerations are not of immediate importance; but if the project proves successful, they will have to be considered. The fact that at one time it was planned to use some or most of these waters for the domestic water supply of Athens suggests that their increased use for irrigation around their point of issue would not damage the water economy of the basin as a whole.

Since Aghia Eleousa is not used for domestic water supplies, and since the area is well provided with water for animals, the fact that it may cease to flow for three or four months after irrigation ceases will cause no difficulty in these respects. Kato-Agoriani spring is used for the domestic water supply of Lilaia village; this water has to be pumped at present, and the increased cost of pumping from a slightly lower level would not be of major importance compared to the gain in agricultural production from the village lands.

The irrigation water would not be rentable if its cost exceeded 0.5 drachmae per cubic metre. This figure is based on an exhaustive study by the Ministry of Agriculture (Palaiologos, 1960), dealing with the cost of irrigation water pumped from boreholes. From Table XXIV of this valuable study, the highest possible prices of water for different crops, grown under four different, as well as average, conditions are given. The figures for crops under «Average Conditions» have been extracted and may be listed as follows:

Maize	0.26 drachmae per cubic metre
Cotton	0.50 drachmae per cubic metre
Sugar beet	0.56 drachmae per cubic metre
Alfalfa	0.58 drachmae per cubic metre
Potatoes	0.63 drachmae per cubic metre

Vegetables	0.64 drachmae per cubic metre
Grapes	1.46 drachmae per cubic metre
Fruits	1.27 drachmae per cubic metre

The higher figures on this list may be excluded, since it is best to calculate that the water will be used for cotton, sugar beet, alfalfa and similar crops. With some 9 million cubic metres of water for sale, a price of just 0.325 drachmae per cubic metre (leaving a good profit margin to the farmer) would bring in a yearly revenue of 3,000,000 drachmae, equivalent to US. $ 100,000. Such an annual income would cover operating costs and permit of rapid amortization of the capital investment which such a scheme would appear to require.

This is not the place to go into details of costs and economics; it is sufficient to show that the scheme is feasible as much in its economic as in its technical aspects.

5. Acknowledgments and bibliography

5.1. *Acknowledgments*

The author's acknowledgments are due to the Special Fund of the United Nations and to the Institute for Geology and Subsurface Research for permission to present this paper to the meeting. The work forms part of an investigation into the groundwater resources of the karstic limestones of Greece. The basic hydrological data on spring flow has kindly been supplied by Mr. A. Georgalas, while information on the economic limits of irrigation water has been supplied by Mr. I. Paleologs.

BIBLIOGRAPHY

Abd-el-al, Ibrahim (1952) «Statics and Dynamics of Water in the Syro-Lebanese Limestone Massifs». UNESCO Ankara Symposium on Arid Zone Hydrology, p.p. 60-76.

Ambroggi, R.P., Archambault, J., Burdon, D.J., Richardson R. and Wager, R. (1958) «Investigation of Groundwater Resources in Karstic Limestone, with Special Reference to Creece», FAO/59/8/6114, Rome.

Aronis, G. (1959) «The Need for Karstic Groundwater Exploration in Greece», Inst. for Geology and Subsurface Research, Vol. V., nº. 5.

Ayoub, Mohamed el Sayed (1952) «Control of Underground Water Resources to Protect the Hydrological Balance and Ensure Intensive Organized Utilization» UNESCO Ankara Symposium on Arid Zone Hydrology, pp. 115-124.

Burdon, D.J. and Safadi, C. (1961). «Ras-el-Ain : The Great Karst Spring of Mesopotamia» (in press).

Maillet, Edmond (1905) «Essais d'Hydraulique Souterraine et Fluviale», Librairie Scientifique Hermann, Paris.

Mariolopoulos, E.G. and Carapiperis, L.N. (1954) «Precipitation in Greece», Govt, Printer, Athens.

Paleologos, I, (1960) «Method of Investigating the Economic Limits of Drilling for Groundwater», Ministry of Agriculture, Athens.

Papastamatiou, J.N. (1955) «Bauxite Deposits in Parnassos-Chiona» Institute for Geology and Susurface Research, Report nº. 21.

Walker, E.H. (1956) «Reservoir capacity of Mississipian Limestones in the Hopkinsville Quadrangle, Kontucky». Bull. Geol. Soc. America, Vol. 67, pp. 1431-1440.

GROUND-WATER RECHARGE BY DIRECT INFILTRATION OF RAINFALL

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SUMMARY

On large areas the source of water to recharge groundwater is precipitation. The process of infiltration being very compound, in order to obtain reliable quantitative values it is advisable to execute water-household investigations based on hydrologic observations on areas having simple conditions. This paper contains data observed during 10 years on two experimental areas—one of them being a karstland, the other a sand-ridge—and the conclusions drawn therefrom. These can be arranged in groups as follows:

a) Annual *quantity of groundwater recharge* and monthly distribution thereof under different circumstances.

b) In case of infiltration through *fissured rocks* a *perennial recharge* of more considerable quantity appears, than in *granular, sedimentary rocks.*

c) In this latter case evaporation of groundwater is significant owing to the effect of fluctuations in soil temperature, whereby *periodical replenishment* will be exhausted.

d) According to the observation data, in granular, sedimentary rocks a more considerable *perennial groundwater recharge* comes into being, when annual sum of precipitation is greater, than 77-80 per cent of the value E_0 computed by the formula of PENMAN.

RÉSUMÉ

Sur territoires étendus c'est la précipitation qui fournit la principale alimentation pour l'eau souterraine. Le processus de l'infiltration est bien complexe, de ce fait, pour déterminer des valeurs réelles, il est à recommander de faire des analyses de bilan d'eau en vertu d'observations hydrologiques sur des régions disposant de simples caractéristiques. Cette étude renferme les données d'observation de 10 ans concernant deux territoires expérimentaux, l'un des deux étant une région karstique, l'autre un plateau de sable. Ces données peuvent être groupées de la manière suivante :

a) En cas de dispositions différentes *la quantité* annuelle du *remplissage de l'eau souterraine* et sa distribution mensuelle.

b) En cas d'une infiltration se produisant à travers *des roches crevassées* un plus grand remplissage persistant se produit que dans *les roches granulaires et sédimentaires.*

c) En ce qui concerne ces dernières, l'évaporation de l'eau souterraine est bien considérable à la suite de l'effet des fluctuations des températures du sol, par quoi *le remplissage périodique* sera consommé.

d) D'après les données d'observation c'est *un remplissage plus considérable et prolongé* qui se produit dans les roches granulaires et sédimentaires, si la somme annuelle de la précipitation fait plus, que 77-80 pour cent de la valeur E_0 calculée avec la formule de PENMAN.

1. INTRODUCTION

At development of groundwater resources three grades should be mentioned. Some decades ago water had not been yet required in great quantities. Thus, in the first grade of development of groundwater resources the problem to be solved had been rather to determine where water was to be found, than to establish how much thereof could be available. In the second grade, however, it is required to obtain informations regarding total water resources.

Main task of the present is yet represented by the problem, *how much water can be exploited and how long a certain water withdrawal can be applied without* *exhaustion of the supply*. For determining this latter question, estimations concerning *groundwater recharge and replenishment* are needed.

When classifying groundwater resources—included both shallow groundwater and artesian one—centurial or passive resources, then those taking part in the hydrologic cycle can separately be discussed. A direct replenishment appears but in the latter case. It is precipitation, that may be considered as main source of water to recharge groundwater. Absorption from surface waters is usually restricted only to a narrower strip. Recharge derived from precipitation can arise from *local rainfall* or from that of an outcrop area considered as *principal intake area* of the aquifer.

The process of infiltration is very compound. According to meteorologic factors and to the variety of vegetation and rocks, the run of seepage in time as well as the quantitative values may be highly different. Study of the mechanism of the intake into aquifers is partly furthered by experiments performed with lysimeters and with different gauges of seepage, partly by water-household investigations based on hydrologic observations.

We are going to present below the results of several hydrologic observations carried out for the purpose of determining quantitative values of infiltration due to precipitation, as well as their distribution in time. The aim of these observations was to determine the following values:

1. *How much is the* annual *quantity of deep seepage* i.e. that of infiltration, which reaches the groundwater table and how does it distribute monthly?

2. How does groundwater replenishment *change according to the depth of water table*?

3. What kind of difference exists between recharge taking place in *fissured rocks* and that occurring *in granular ones*?

4. *How much is minimum amount of precipitation*, whereat groundwater replenishment begins and what quantity of precipitation is needed for inducing not only a *periodical* recharge but a *long-lasting*, *perennial* one?

2. RESULTS OF OBSERVATIONS

For direct observation of groundwater recharge those areas are primarily suitable, where water-household is relatively simple and some of the individual hydrologic factors can be neglected. On lowlands principal recharge areas are usually represented by surface sand-layers of larger extension, while on mountain regions by fissured, cavernous rocks, included karstlands. In Hungary, within the framework of hydrologic observations enlarged upon the whole country, detailed experiments are carried out on such areas, where surface runoff is practically negligible, consequently the maximum of groundwater replenishment due to infiltration of precipitation can be determined. *Results of observations executed on two experimental areas* are described below.

On a typical karstland of Hungary, in the Mecsek Mountains detailed measurements have been carried out by H. KESSLER (2). He has determined the replenishment of resources due to precipitation upon base of wateryield of the Tettye-spring (a tubular spring). The catchment area has an extension of 5 sq.km, the topography of the ground—in an average height of 500 m above sea level—shows typical features of the karstification. About 75 per cent of the surface is covered by beech wood.

In the Hungarian Plain detailed groundwater observations have been carried out since years. Within this area a great number of territories can be found, where both surface and subsurface runoff are rather insignificant for being neglected, or just equal to zero. Thus, by the aid of variations in resources computed on the basis of groundwater observations, replenishment due to precipitation can be calculated. Detailed tests are executed in the *Experimental Station* having an extension of 1 sq.km, lying on *the sand-plateau between the Danube and Tisza.* Making no mention of the details (8,10), we deal with measurement results of the last 10 water years (1-XI-1950/ 31-X-1960).

In Fig. 1 integral curves of the *yearly average recharge* measured on the karstland, as well as on the sand-plateau (in case of a groundwater table lying in a depth of 4 m) have been illustrated. On the karstic area the 10 years average of the annual sum of precipitation was observed to be *716 mm*, while on the sandridge *582 mm*. The difference in precipitations is comparatively insignificant, and yet disagreements appearing in groundwater recharge are considerable. In the winter half year, from 1-XI till 30-IV infiltration is similar on both areas, in the summer period, however, replenishment proceeds on the karstland (though with less intensity), while on the sand-ridge in addition to the ceasing of infiltration also recharge due to the winter period will be consumed by evapotranspiration.

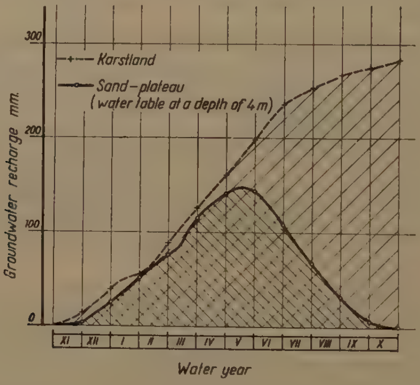

Fig. 1 — Integral curves of the yearly average recharge measured on the karstland, as well as on the sand-plateau. (10 years average, 1951-1960).

In Table 1 monthly, half-yearly and yearly values of 10 years average are summarized concerning sum of precipitation, mean air temperature, groundwater recharge (in mm and l/s.sq.km) and infiltration percentage. This latter is expressed by the relative number of recharge (R) and precipitation (P):

$$\text{infiltration percentage} = \frac{R}{P}\,100$$

Monthly variations of infiltration percentage are shown in Fig. 2

The values made known here are rough measurement results. When estimating groundwater resources, in order to be able to draw conclusions for replenishment to be expected, it is recommended to establish relations between infiltration and the most important influencing factors.

3. RELATIONSHIP BETWEEN GROUNDWATER RECHARGE AND PRECIPITATION

In possession of hydrologic observations carried out carefully, *in most cases a good relationship can be pointed out between precipitation and groundwater recharge.* It must be emphasized that when making investigations into this relationship, a qualitative analysis should be applied in an increased degree. At the complicated process of water household, out of the numerous factors two ones are selected, the

TABLE 1

Observed values. Average of ten-years (1951-1960)

	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	Winter half year I.XI-30.IV	Summer half year 1.V-31.X	Annual total
Karstland															
Air temperat. T, C°	+ 4,1	+ 1,7	− 1,2	− 1,0	+ 3,4	+ 8,9	+13,6	+17,4	+19,5	+19,5	+15,8	+10,3	+ 2,7	+ 16,0	+ 9,4
Precipitation P, mm	60,6	59,0	40,4	42,4	34,5	59,5	70,3	104,9	78,5	62,1	51,0	53,1	296	420	716
Groundwater recharge R, mm	13,5	25,5	16,2	33,5	37,2	34,3	38,0	37,7	17,7	13,8	7,6	8,3	160	123	283
Groundwater recharge l/s. km²	5,21	9,53	6,05	13,85	13,90	13,22	14,20	14,53	6,61	5,15	2,93	3,10	10,24	7,74	8,99
Infiltration percentage *R*/*P* ×100, %	22,3	43,2	40,1	79,0	107,8	57,7	54,1	36,0	22,6	22,2	14,9	15,6	54,1	29,3	39,6
Sand-plateau															
Air temperat. T, C°	+ 5,0	+ 1,8	− 1,3	− 0,2	+ 4,6	+10,7	+15,6	+19,8	+21,5	+20,6	+16,0	+10,3	+ 3,4	+ 17,3	+10,4
Precipitation P, mm	52,3	51,5	38,5	38,7	30,8	39,2	71,4	74,3	67,7	48,8	29,1	39,9	251	331	582
Water table at a depth of 3 m															
Groundwater recharge R, mm	22,4	22,8	29,6	19,8	29,4	7,7	− 1,4	−29,4	−31,5	−35,2	−28,7	− 3,0	132	−129	0
Groundwater recharges l/s. km²	8,65	8,52	11,07	8,20	10,97	2,97	–	–	–	–	–	–	8,46	–	–
Infiltration percentage *R*/ *P*+ 100,%	42,9	44,3	77,0	51,1	95,5	19,6	–	–	–	–	–	–	52,5	–	–
Water table at a depth of 4 m															
Groundwater recharge R, mm	3,5	21,6	26,4	24,1	39,2	25,6	3,5	−35,9	−41,1	−35,2	−26,8	− 6,3	140	− 142	0
Groundwater recharge l/s.km²	1,35	8,06	9,87	10,0	14,62	9,89	1,31	–	–	–	–	–	8,97	–	–
Infiltration percentage *R*/*P* × 100,%	6,7	42,0	68,6	62,3	127,2	65,4	4,9	–	–	–	–	–	55,8	–	–

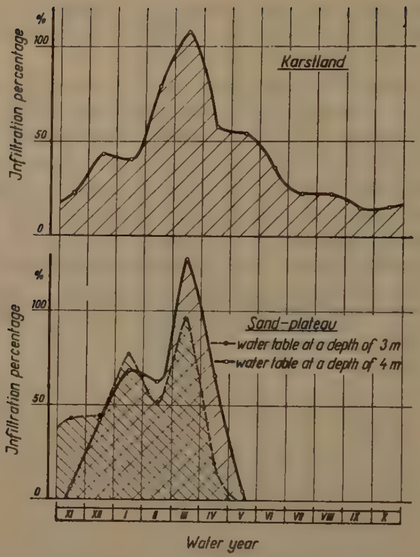

Fig. 2 — Monthly variations of infiltration percentage. (10 years average, 1951-1960).

relation of which should be searched for. It is evident that connected pairs of values —according to the effectiveness of the other factors influencing the water household —will scatter. In agreement with our experiences, an unequivocal relationship appears between rainfall and groundwater recharge in those periods, when the other factors exert a similar effect.

Short periods (days, weeks) are not suitable for determining the realtionship. However, by taking into consideration longer periods, in most cases satisfactory results can be attained. In our country the most suitable period is the winter half year (1-XI–30-IV), this being the principal season for replenishment of groundwater resources and having been proved by numerous examinations, that in case of a shallow groundwater unanimous relations may be established [8 10].

Actual evapotranspiration in Hungary amounts to *100-120 mm* in the winter period and this value varies between relatively smaller limits. Accordingly, more than 50 per cent of the winter precipitation infiltrates and a close relationship can be pointed out between rainfall and replenishment [2 8 10]. The relationship determined for the karstland is shown in *Fig. 3.*

In the summer period evapotranspiration varies already to a greater extent, in consequence of which values determined for the whole year show a more considerable scattering (Fig. 3). The scattering grade has been reduced by H. Kessler by means of introducing determinative precipitation rate [2]. Similar results can be attained, if the sum of precipitation is computed for a period beginning earlier with a month (1.X.-30.IX) and in this way we take possession of a relationship characterizing adequately the average conditions (Fig. 3). Principal reason of the scatterings is assumed to be the different rainfall distributions in the single years.

According to the relations determined for the observed karstland *a considerable, perennial recharge* arises in every case, when precipitation of the winter half year amounts to be more than *136 mm,* that of the summer period more than *297 mm* and the annual rainfall more than *433 mm.*

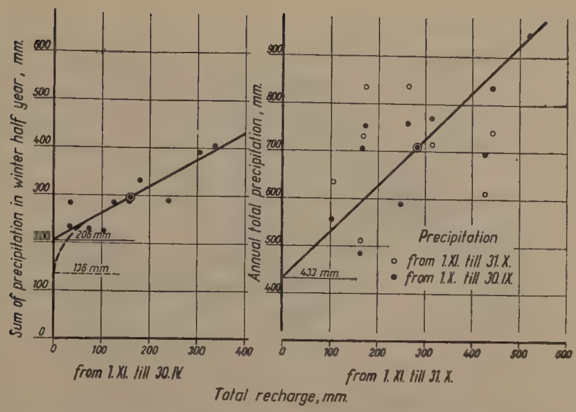

Fig. 3 — Relationship between precipitation and groundwater recharge on karstland. (10 years average, 1951-1960).

Average annual recharge is characterized by the following empirical relationship:

$$R = P - 433 \qquad [\text{mm}]$$

On this karstic area covered in 75 per cent by beech wood, the 10 years average of actual evapotranspiration mounted up to *433 mm.*

It is *characteristic for karstlands* and in general for areas covered by fissured, cavernous rocks, that every water quantity infiltrated from precipitation results in a *perennial, continuous replenishment of resources.* In present case it appears in water yield of a spring.

An essential difference can be observed, however, in case of a recharge due to infiltration taking place *through loose, granular, sedimentary rocks.* In the winter period, when potential evaporation and together with this the actual one can be taken for insignificant, replenishment is similar to that of the fissured rocks (Figs. 1, 2, Table 1). But *winter replenishment is only periodical* and during summer it can enterely be exhausted by evapotranspiration. In case of granular, sedimentary rocks one can eventually draw false conclusions, if replenishment arisen in the winter period or infiltration collected by the lysimeters are considered to be perennial groundwater recharge.

In Fig. 4, variations in the annual groundwater resources observed on the sand-plateau are shown in function of the yearly precipitation amount, relating to a groundwater table lying in an average depth of 3 m. Groundwater resources are in state of equilibrium, neither perennial recharge, nor decrease can be experienced, if the annual sum of precipitation runs to about *580 mm.* Ten years average of the actual evapotranspiration had been *580 mm* on the experimental area [8,10]. In the winter period an increase in the water resources could be observed in every year, which however had been consumed in the summer period (without subsurface runoff or water exploitation). A periodical groundwater replenishment comes into being, when annual precipitation amounts to more than *580 mm,* which does not mean however a perennial recharge, being exhausted by evapotranspiration in rainless years (Fig. 4).

4. INFLUENCE OF DEPTH OF GROUNDWATER TABLE

Making a comparison between the values of records presented above and those of infiltration and evaporation determined by lysimeter measurements, contradictions

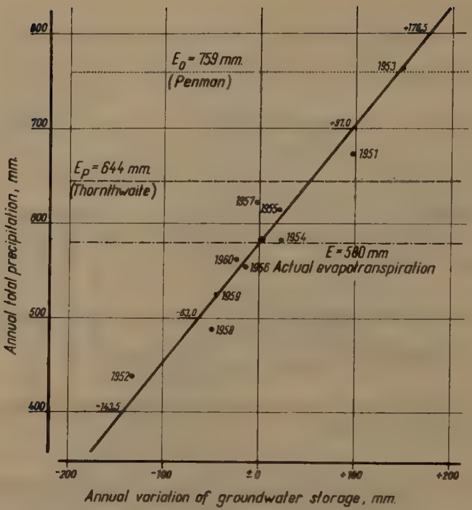

Fig. 4 — Relationship between annual variation of groundwater storage and annual total precipitation on sand-plateau. The groundwater table lies in an average depth of 3 m.

are arising at first consideration. Lowlands of Hungary belong to the subhumid climatic group on the basis of the *Thornthwaite index* P/E [6] (Index $P/E = 45$-48) and yet a perennial groundwater recharge does not appear in the granular, sedimentary rocks, as proved by water-household examinations. Groundwater household is in state of equilibrium, namely in such manner that with increasing depth of the groundwater table the annual groundwater exchange due to the periodical replenisment of the winter period is decreasing and in a depth of 7-10 m even periodical recharge comes to an end. In Fig. 5 average annual exchange of groundwater observed on the Hungarian Plain has been represented plotted against the values of depth. Scattering of the points is caused by the various infiltration possibilities and by the different degrees of the vegetation-cover.

If groundwater table lies deeper than 7-10 m, deep seepage reaching the groundwater table under conditions of the occuring rainfall distribution cannot come into validity. Though in a smaller depth periodical recharge can be formed, this will be consumed by evapotranspiration. Actual evaporation is prevailing up to a larger depth, than it could be concluded from lysimeter observations.

5. EFFECT OF EVAPORATION UPON PERENNIAL GROUNDWATER RECHARGE

From the view-point of estimating the efficiency of perennial groundwater recharge derived from precipitation and besides that of artificial recharge it is essential to go more deeply into study of groundwater evaporation. Comparability of the actual evaporation values determined under different climatic conditions will be facilitated, if relative values attached to a fictitious, maximum value (potential evaporation) can be used.

For our experimental area laying on the sand-ridge we have determined potential evapotranspiration to be computed by means of the formula of THORNTHWAITE [7] as well as by that of PENMAN [4], having used average values of the 10 years long

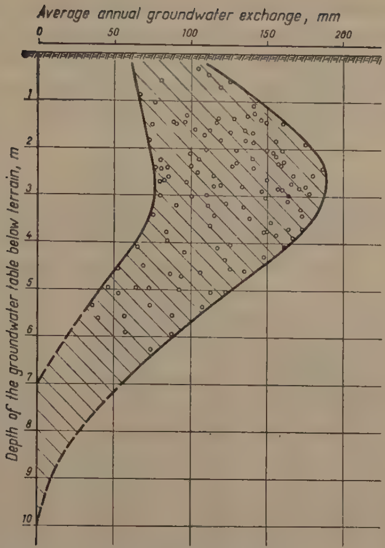

Fig. 5 — Average annual exchange of groundwater observed on the Hungarian Plain as a function of the depth below terrain.

period. In our opinion, the values of potential evapotranspiration computed by different methods [3 4 7], show essential differences and approach more or less the actual evapotranspiration of tests applied for determination of the formulae. For comparative computations we think suitable the formula of PENMAN [4] elaborated for free water surface, according to which:

$$E_0 = \frac{de/dT\, H_0 + \gamma\, E_a}{de/dT + \gamma}$$

and we consider the value to be computed in such way as maximum potential evaporation.

In Table 2 the following values are summarized: values of E_0 computed for the 10 years average on the sand-ridge, actual evapotranspiration (E), the relative number E/E_0, decrease of the summer period in the groundwater storage ($-R$), as well as the relative number thereof compared to the actual and potential evapotranspiration.

Actual evapotranspiration has been both in the winter and summer half year 76-78 per cent of the value E_0 computed by the formula of PENMAN. This is more than potential evapotranspiration computed by the known formula $E_p = fE_0$. Similar establishment was made by MAKKINK too [3].

Considerable part of actual evapotranspiration —25 per cent of the annual sum —has been formed by decrease in the groundwater storage. Upon base of experiments made by lysimeters, in case of a groundwater table lying in a depth of 4 m such an extensive groundwater evaporation would not be expected. In a preceding paper [9] we have pointed out, that by draining off water infiltrated at the lysimeters a soil-prism more or less unwatered is produced, the evaporation of which is less than that of the natural soil layer. In summer a considerable, quick vapour-movement is evolving owing to the effect of fluctuations in soil temperature, and as a consequence of that groundwater storage is decreasing even in a depth of 3-4 m [9 11]. This will be advanced also by the moisture movements arising on account of the effect of capillary potential.

TABLE 2

Computed values. Average of ten-years (1651-1960)

	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	Winter half year 1.XI-30.IV	Summer half year 1.V-31.X	Annual total
Potental evaporat. E_0, mm	9,4	1,9	3,3	11,3	37,9	73,5	110,2	134,3	148,3	124,7	71,6	32,9	137,3	622,0	759,3
Actual evapotranspiration															
E, mm	9,4	1,9	3,3	11,3	37,9	44,0	85,7	110,2	108,8	84,0	55,9	31,2	107,8	475,8	583,6
E/E_0	1	1	1	1	1	0,599	0,778	0,821	0,734	0,674	0,781	0,947	0,785	0,765	0,768
Decrease in the ground-water storage $(-R)$ mm	–	–	–	–	–	–	–	35,9	41,1	35,2	26,8	6,3	–	145,3	145,3
(Water table at a depth of 4 m)															
$(-R)/E_0$	–	–	–	–	–	–	–	0,267	0,277	0,282	0,374	0,192	–	0,234	0,192
$(-R)/E$	–	–	–	–	–	–	–	0,326	0,378	0,419	0,480	0,202	–	0,305	0,250

Thus, it can easily be realized, why only a periodical replenishment will be formed as a rule in granular, sedimentary rocks. On lowland territories of Hungary a «more permanent» groundwater recharge lasting 1-2 years comes about but in those years, when precipitation runs to more than average of many years (550-600 mm) i.e. more than 77-80 per cent of the value E_0 to be computed by the formula of PENMAN (Fig. 6.)

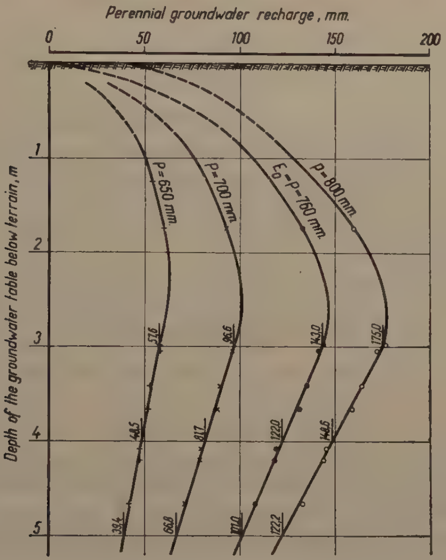

Fig. 6 — Perennial «more permanent» groundwater recharge on Hungarian Plain, when precipitation runs to more than average of many years.

We assume similar regularities to prevail on other areas as well. It should be emphasized, that in case of a fully naked soil similar evaporation losses may occur, as in that of surfaces covered by plants having smaller water requirements, fluctuations in soil temperatures being much more considerable, than in a soil shaded with vegetation, in consequence of which intensive vapour movements and evaporation will be induced.

6. CONCLUSIONS

Finally, we sum up conclusions drawn from the observation data of 10 years as follows:

a) Concerning groundwater recharge derived from precipitation *an essential difference can be experienced depending on, whether infiltration takes place through fissured, creviced rocks or through granular, sedimentary ones.*

In the former case *a perennial groundwater recharge* arises in every period, when rainfall is more than evaporation. Groundwater laying in a deeper level is not consumed by evaporation in rainless periods.

b) As far as granular, sedimentary rocks are concerned, a perennial recharge appears but in the case, when—at a relatively uniform distribution—the yearly sum of precipitation is more, than average yearly evaporation. In order to reach this value, annual precipitation in Hungarian lowlands ought to be more, than 77-80 per cent of the value E_0 computed by the formula of PENMAN. Infiltration taking place in the winter period or amount of infiltration collected by lysimeters shows but the quantity of periodical replenishment.

c) When estimating the recharge of groundwater resources—whether infiltration of local rainfalls, or the principal intake area of aquifer lying on an outcrop territory should be examined—it is advisable to make efforts to determine the quantity of perennial recharge, taken into account evaporation losses.

REFERENCES

[1] FERRIS J.G. and SAYRE A.N., Development of the quantitative approach to ground-water investigations. *Publication n° 44 de l'Association Internationale d'Hydrologie Scientifique.* Assemblée Générale de Toronto, 1957.

[2] KESSLER H., Estimation of subsurface water resources in karstic regions. *Publication n° 44 de l'A.I.H.S.* Assemblée Générale de Toronto, 1957.

[3] MAKKINK G.F., De verdamping uit vegetaties in verband met de formule van Penman. *Verslagen en mededelingen Nr 4* van de commissie voor hydrologisch onderzoek, T.N.O., 1960.

[4] PENMAN H.L., Estimating evaporation. *Transact. Amer. Geophys. Un.*, V. 37, 1956.

[5] PLOTNIKOV N.A. and BOGOMOLOV G.B., Classification of underground water resources and their reflection on maps. *Publication n° 44 de A.I.H.S.*

[6] THORNTHWAITE C.W., An approach towards a rational classification of climate. *Geogr. Rev. V. 38, 1948.*

[7] THORNTHWAITE C.W., MATHER I.R., The water balance. *Drexel Institute of Technology*, Laboratory of Climatology, V. VIII, No. 1, New-Yersey, 1955.

[8] UBELL K., Water-balance of sand-plateau between the rivers Danube and Tisza. *Publication n° 45 de A.I.H.S.*, Assemblée Générale de Toronto, 1957.

[9] UBELL K., Moisture movement in unsaturated soils, with special regard to the utilization of lysimeter observations. *Publication n° 49 de A.I.H.S.* Symposium Hannover-Münden, 1959.

[10] UBELL K., Determination and representation of characteristic data for groundwater household. *Publication n° 52 de A.I.H.S.* Assemblée Générale de Helsinki, 1960.

[11] DE VRIES D.A., Simultaneous transfer of heat and moisture in porous media. *Trans. Amer. Geophys. Union*, V. 39, No. 5, 1958.

GROUND-WATER DILEMMA AT TEBOULBA, TUNISIA

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ABSTRACT

Teboulba's dilemma is that the current rate of pumping from wells is depleting the subterranean reservoir; but the water thus being withdrawn from storage is of better quality than some of the water that replenishes the reservoir, so that even if the rate of withdrawal is reduced, the quality of water in some wells may deteriorate.

In the vicinity of Teboulba, which lies in the Sahel region along the coast of central Tunisia, there is a shallow body of usable ground water which is bounded in four directions by saline waters. Withdrawals to date have created hydraulic gradients favorable for encroachment of sea water from the Mediterranean and of salt water from the Sebkha de Moknine, a saline lake. At depths greater than about 100 m (meters) the ground water is slightly more mineralized than at lesser depths, and brine aquifers are encountered below 160 m. Water entering the shallow body from above — by slow drainage from fine-grained sediments and by recharge from precipitation — may also be mineralized. Optimum utilization of this ground-water body cannot be achieved by adherence to the principle of perennial yield. Instead, the fresh water should be developed by mining techniques, including blending of waters to produce a product of usable quality, and depletion at a rate sufficient to prevent excessive contamination. Thus this water is classified as a non-replenishable resource, which will last for several years and perhaps for several decades (depending upon the rate of depletion), but which cannot be counted on for sustained yield.

RÉSUMÉ

Le dilemne de Téboulba est causé par le fait que le taux courant de pompage des puits est en train d'épuiser le réservoir souterrain; mais l'eau ainsi tirée est de meilleure qualité que celle qui recharge la nappe, donc même si le taux de puisage est réduit la qualité de l'eau de certains puits peut se détériorer.

Dans la région de Téboulba, le long de la côte du centre de la Tunisie, il y a une nappe peu profonde d'eau de bonne qualité qui est bordée des 4 côtés par des eaux salées. A ce jour les eaux tirées ont donné à la nappe une pente favorable à l'intrusion des eaux de la mer et des eaux de la sebkha de Moknine. A des profondeurs supérieures à 100 m l'eau souterraine est sensiblement plus minéralisée que celle des zones de moindre profondeur. Les eaux saumâtres se rencontrent au-delà de 160 m de profondeur. Les eaux alimentant la nappe de par en haut — par infiltration lente à travers les sédiments fins après les précipitations — peuvent aussi être minéralisées. La meilleure utilisation de cette nappe ne peut être acquise en se basant sur le principe du bilan d'eau. Au lieu de cela, les eaux potables devraient être développées par l'exploitation, c'est-à-dire mélanger les eaux pour obtenir un produit utilisable, et par un puisage à un rythme suffisant pour prévenir une contamination excessive. Ainsi cette eau est considérée comme une ressource non renouvelable qui peut durer plusieurs années et même plusieurs décades (évidemment cela dépend du rythme d'utilisation), mais sur laquelle on ne peut compter pour avoir un débit soutenu.

INTRODUCTION

Our study of the ground-water conditions in the vicinity of Teboulba covers an area less than 40 km^2 (square kilometers), which is an infinitesimal part of Africa, and miniscule even for Tunisia (slide 1). This area is noteworthy because the inhabitants, having depleted the ground-water reservoir to some extent by withdrawals for irrigation, appear not to have any suitable alternative to continuing this depletion until the reservoir is exhausted; but if they had never started this depletion they would never have obtained the benefits from the fresh water that they are now pumping. To the authors this area is also noteworthy because the conclusions we now reach concerning it are notably different from those we might have made after a brief inspection of the area and available records pertaining to it.

2. PHYSICAL ENVIRONMENT

The area considered in this report is about 10 km long, extending from the towns of Sayada, Ksar Héllal, and Moknine on the west to Bekalta on the east; it is about 4 km. wide, and is bordered on the north by the Mediterranean Sea. More than 6 km. of the south border of the area is formed by the Sebkha de Moknine, a saline lake that has a bed 5 to 9 m below sea level and an areal extent of about 50 km² in winter, much less in summer.

The central part of the area between the two salt-water bodies is relatively flat, with maximum altitude ranging from 30 m near Ksar-Hellal to 20 m at Teboulba and 12 m near Bekalta. Generally the descent from this plateau to the Mediterranean is rather abrupt and within a few hundred meters of the shore, but several small ephemeral streams have cut into the plateau for distances of half a kilometer or more. The southward descent from the plateau to the Sebkha is more gradual, generally extending over a kilometer; several streams have established channels approaching 2 km. in length, but their valleys are broader and shallower than those draining to the Mediterranean. There are no perennial streams and no fresh-water springs in the area. All streams are dry except during runoff from exceptional storms.

Geology: – The sediments that crop out in the Teboulba area and those penetrated by existing wells, are all of Quaternary age. These Quaternary sediments are underlain by Tertiary sediments of considerable thickness, and it is possible that the fresh-water reservoir in the Quaternary sediments near Teboulba extends downward somewhat into the Pliocene. However, the permeable zones at greater depth in the Tertiary probably bear saline water, according to deep borings elsewhere in the Sahel region. In this paper we are concerned only with the shallow ground-water body.

The "croûte calcaire" or lime hardpan, dominates the region, cropping out along the northern edge of the plateau near the coast, (slide 2) underlying the plateau soils everywhere at very shallow depth, and lying at somewhat greater depth under the slopes that drain to the Sebkha.

The lime hardpan provides the material for practically all buildings and some subterranean dwellings, for the walls and super-structures of dug wells, for fences, and for cemented conduits to carry water from wells to gardens. It forms the roofs for tunnels at the lower ends of the towpaths at most wells. And the large remainder provides numerous handicaps to agriculture.

Aside from the "croûte calcaire", the Quaternary sediments that appear on the surface are of limited areal extent. They include 1) the alluvium in the stream valleys and colluvium on the steeper slopes, both derived in large part from the "croûte calcaire"; 2) the sands along the Mediterranean coast, including littoral, eolian, and fluvial deposits; 3) lacustrine clays along the borders ot the Sebkha; and 4) fluvial and eolian sands, especially between Teboulba and the Sebkha, but also in some other parts of the area.

According to records from borings, dug wells and tunnels, the uppermost "croûte calcaire" ranges in thickness from 2 to 15 m. At greater depths the Quaternary sediments are dominantly clay and silt, with some layers of lime hardpan down to depths as great as 35 meters, and with numerous thin beds and lenses of fine sand which constitute the aquifers.

Soils: – As mapped by Cointepas (1959) the soils in most of the Teboulba area are clayey, highly calcareous, and laden with fragments of the "croûte calcaire". On the plateau the soil generally has a depth less than 0.4 meter. Along the slopes descending toward the Sebkha the soil commonly exceeds 0.8 meter in depth, but there too it is generally underlain by the hardpan. Sandy soils are of limited extent, occurring chiefly along the Mediterranean coast and along the slopes bordering the Sebkha. There are also saline clay soils bordering the Sebkha. Cointepas has classified practically all these soils as mediocre. The thin soils underlain by lime hardpan are considered by him to be best adapted to olive culture, and he recommends against extensive irrigation of those soils because of the danger ot waterlogging (engorgement) above the "impermeable" hardpan.

Climate – In 31 years of record the average annual rainfall at Teboulba has been 375 mm (millimeters), of which 330 mm has been received during the seven months September to March. On the average, October is the wettest month, and there is thereafter a gradual and progressive decline in precipitation for the next 6 months. The area has a fall-and-winter growing season with very rare frost, and an arid summer with more humidity in the atmosphere and lower maximum temperatures than inland areas, because of the Mediterranean influence. Nevertheless, the average annual evaporation (measured at Sousse) is more than three times as great as the average annual precipitation, and the climate of the Sahel region is distinctly on the arid side. Winds that may provide some hazard for agriculture include the occasional hot siroccos from the south during the summer, and the more frequent north winds at other times of the year.

The actual weather includes wide variations from the average, particularly in precipitation, which has ranged from 141 mm in the agricultural year 1946 to 906 mm in 1932. In more than one-fourth of the years of record the precipitation has been less than 250 mm, and in more than one-fourth of the years it has exceeded 450 mm. Furthermore, the record from Teboulba and the longer record from Sousse indicate an alternation of wetter periods (1890-94, 1902-07, 1919-21, 1932-36, 1949-52, 1956-59) and of more extended periods of drought (slide 3). In the period of record the monthly precipitation at Teboulba has been 200 mm or more in 6 months, all in the three wettest years, and all but one in the autumn. Such heavy storms in the fall, following the long summer dry season, are conducive to floods and erosion.

3. HUMAN ADAPTATION TO ENVIRONMENT

In many respects the environment is a challenge to mankind, and mankind has responded to this challenge with varying degrees of ingenuity. Several of these adaptations doubtless were made centuries ago. For example the development of the olive as the principal agricultural product because it can adapt to the marginal and variable water supply. The building of dikes or levees around individual olive groves or subdivisions is also a well-established practice, to hold the raindrop where it falls and obtain the maximum benefit from limited precipitation. Several wells have been pointed out as "Roman". They appear to be ancient indeed, but we do not have enough background in archeology to verify or refute the claims.

Although we cannot identify a Roman well, we are aware that the limited water resources throughout Tunisia have sustained peoples of numerous civilizations throughout more than 2,000 years of recorded history, by means of streams, springs, galleries, cisterns, wells and the moisture in the soil that produces crops. To the extent that these sources provide a sustained yield throughout the centuries, past or future, they must have been and must continue to be replenished by precipitation. Throughout Tunisia the maintenance of a hydrologic balance by limiting the withdrawals from wells to the amount that can be replenished is fundamental in the philosophy of administration of the water resources – and inevitably so, if we are to attempt to see as far into the future as we are able to look into the past.

Population – As of 1959, the population of the Teboulba area was about 65,000, of which about 44,000 were concentrated in the cities of Moknine (20,000), Ksar Hellal (8,300), Teboulba (6,200), Sayada (5,700) and Bekalta (3,300). There is relatively little industrial development in any of these towns, and the urbanites therefore are almost as dependent upon the agricultural economy as their rural brethren.

Agricultural Economy – Olives are the principal product of the area, and aerial photographs indicate approximately 70 percent of the land is covered by olive groves, especially on the plateau. The land between the olive trees in many places is planted in forage. Small gardens may also be planted for the winter growing season, and in years with a favorable amount and distribution of rainfall these may yield good crops for market without irrigation. Dry farming, however, is hazardous because of the frequency of drought years.

Irrigated tracts of vegetables and fruits, sometimes among the olive groves and sometimes replacing them, are numerous and becoming more so (slides 5 and 4). All water for irrigation comes from dug wells. Having catalogued 560 wells, we estimate that there must be at least a thousand within the 40 km² area (slide 6). Water is withdrawn from most of these wells in dalous (leather bags) by camels or oxen (slide 7 and 8). More than 50 wells are currently equipped with motor - driven pumps; 45 of these are west of Teboulba and within 3 km of the town (slide 9). The development of water for irrigation has provided assurance of satisfactory crops each year, independent of the vagaries of precipitation. This is of especial value to the Teboulba area, which can thus export winter vegetables and fruits as first arrivals on European markets.

4. EFFECTS OF GROUND-WATER WITHDRAWAL

In the inventory of wells in Tunisia developed by the Groupe d'Hydraulique et des Aménagements Ruraux (HAR) of the Tunisian Secretariat d'Etat à l'Agriculture, some wells were catalogued in the Teboulba area as early as 1895. A study of the area was begun in May 1940 and halted rather abruptly the same year because of World War II. During that study 94 wells were inventoried, and samples of water from each were analyzed. In 1960 the current study was begun by revisiting each of the 94 wells that had been catalogued in 1940.

Status in 1940 – The static levels in the 94 wells visited in 1940 defined a surface that could be depicted but not satisfactorily explained, except to say that the water table must have been highly irregular. There was an indication of a ground-water ridge extending eastward from Ksar Hellal, with a crest about 10 m above sea level at the town, and descending to sea level avout 4 km to the east. Farther east, near Teboulba, there was a depression about 2 km in diameter where the static levels were more than 5 m below sea level, and in ten wells the water levels were 10 to 18 meters below sea level. Except along this central ridge and depression, the water levels in wells were generally within a few meters of sea level. In a broad area west of Teboulba and continuing along the coast to Sayada, and another area northeast of Moknine, the sampled waters had less than 2,000 ppm (parts per million) of dissolved solids. However, in an area extending from Teboulba to the sea, and a smaller area within a kilometer of the Sebkha, the dissolved solids in the waters exceeded 4,000 ppm.

Changes from 1940 to 1960 – When the same 94 wells were revisited in 1960, it was evident that withdrawals by pumps and "dalous" must indeed be creating irregularities in the water table. In 1960, the ground-water ridge near Ksar Nellal was little changed, but it was cut off sharply to the east. The depression was little changed near Teboulba, but it had been extended westward and deepened in the western part.

In the area of greatest withdrawal, where water levels in wells had declined markedly, there were only slight changes in salinity of the water from 1940 to 1960. In wells within a kilometer of the Mediterranean, and also within a kilometer of the Sebkha, there had been little or no decline in static level, but the salinity had increased since 1940. Also, in several wells remote from the sea, including some along the ground-water ridge near Ksar Hellal, the salinity had increased since 1940.

The increasing salinity of water in wells near the sea and near the Sebkha might be taken es evidence of salt-water encroachment toward the cone of depression, which in 1960 had a maximum depth more than 30 m below sea level. But this simple explanation left many unexplained details in the hydrologic picture: the wells remote from sea or Sebkha, with static level several meters above sea level, where salinity had increased during the twenty years; the irregularity in pattern of salinity and changes of salinity in wells near the sea; the differences in static level and in salinity of water in adjacent wells having different depths; the basis for abandonment of wells. Starting from the assumption that these wells had been abandoned because their water was too salty, we began to suspect instead that the water became too salty because the wells were abandoned.

It became obvious that the 94 wells which we had hoped would provide sufficient data to portray the hydrologic conditions in the 40 km² area were inadequate for the purpose. We decided therefore to collect data for every well in the area — a decision that was modified after our inventory passed 500 and we saw the magnitude of the task remaining.

Status in March 1961 – Leveling has not yet been completed to the newly catalogued wells, and we therefore can offer only a map showing depth to water below land surface (slide 10). In most of the area, static levels in wells were more than 20 meters below the land surface, and therefore below sea level. In an area of about 5 km² west of Teboulba — where most of the motor-driven pumps are located — the static levels in wells were 30 to 55 m below the surface. Smaller depressions have developed around pumped wells near Moknine and near Sayada, and also around wells where there is heavy withdrawal by "dalous" for irrigation about 2 km east of Ksar Hellal. Water levels are within 10 m of the land surface in an area extending east from Ksar Hellal for about 2 km. Measurements of conductivity of the water in wells during March 1961 (slide 11) indicated that the water pumped from the depression west of Teboulba is the least mineralized (600 to 2,000 ppm) in the area. Water of good quality (less than 3,000 ppm) is found also in wells in other areas of heavy withdrawal — at Moknine, at Sayada, and east of Ksar Hellal; also in wells along a narrow band parallel to the sea and corresponding in part to areas of outcrop of the lime hardpan, and a broader band extending from Teboulba toward Bekalta under the plateau.

The section extending eastward from Ksar Hellal to the sea (slide 12) crosses the area of shallow water table, the deepest part of the Teboulba pumping depression, and also an area north-east of Teboulba where most wells have been abandoned because of high salinity (5,000 to 8,000 ppm) of the water. Within the Teboulba pumping district along this section there are several wells in which the water level stands several meters above the piezometric surface depicted by other wells in the vicinity.

5. PROBLEMS OF WATER QUALITY

In numerous parts of the Teboulba area, wells are not used because the salinity of their water is too great for use in irrigation. Some of these wells encountered saline water when first dug, others originally yielded fresh water and may have been used for many years before the salinity became excessive. The sources of this salinity, and particularly the reasons for the changes, are of critical importance in managing the ground-water reservoir to provide the optimum quantity of usable water. That reservoir — containing water with modest amounts of calcium, magnesium, sodium and chloride — in bounded in several directions by more saline waters; the sea, the Sebkha, the underlying saline aquifers, and the overlying sediments should all be considered as to their potentialities for contamination of the fresh water.

Sea-Water Instrusion – About 120 meters inland from the newly constructed breakwater northwest of Teboulba, there is a well whose water has a salt concentration about 80 percent of that of the sea. About 250 meters from the shore another well has water with about 40 percent of the concentration of sea water. Here is evidently an example of sea-water intrusion which has not yet penetrated as far inland as 500 meters, where a third well contains only about 3,000 ppm of dissolved salts, comparable to ground-water farther inland and only 7 percent of the concentration of sea-water.

Along a section 500 meters from the Mediterranean shore and parallel to it (slide 13) the static levels in wells generally are above sea level, except where this section crosses the pumping depression northwest of Teboulba and the static levels are 10 to 30 meters below sea level. The salt concentrations in wells along this section, as indicated by conductivity measurements, are generally similar to those of ground-water farther inland. Adjacent to the pumping district, where the static levels are below sea level and where gradients are presumably favorable for sea-water intrusion, the water quality is superior to that in other parts of the section. Northeast of Teboulba this section passes through an area where the waters from all wells have more than 5,000 ppm of dissolved solids. Even here, however, the evidence for sea-water intrusion is not clear, because the salinity does not decrease progressively with increasing distance from the sea.

Overlying sediments – The water table is more than 10 meters above sea level — higher than in any other part of the Teboulba area, — in an area extending east from Ksar Hellal for about 2 km. The quality of water obtained from wells tapping this ground-water ridge is inferior to that in deeper wells to the north, south, and east. It is unlikely that this water and its dissolved mineral matter can come from underlying sediments, but boring planned in the area will provide more information on that. Because lateral inflow is also inconceivable, the most likely source of the water is by downward movement, and the dissolved solids, generally 3,000 to 7.000 ppm, must have been derived from the overlying sediments.

Within the pumping district several shallow wells have static levels several meters above those in adjacent deeper wells. These wells tap water which apparently rests on a relatively impermeable bed and was probably left by the descent of the main water table. However, the water may be draining slowly from overlying sediments. The water in these shallow wells commonly has less dissolved solids than that in adjacent deeper wells and may be replenished in part by precipitation.

In the small areas northeast of Ksar Hellal where withdrawals have lowered the water table more than 35 meters below the land surface, the water is of better quality than in the surrounding area where the water table is 10 to 30 meters below the land surface. And in the vicinity of Teboulba the wells pumped by motor commonly have water of slightly better quality than that in adjacent wells where there is little or no withdrawal. These slight differences in quality of water related to discharge may be an indication of variations in quality within the sediments: better in the permeable sands, which yield water rapidly to the wells; poorer in the less permeable sils and clays, which drain more slowly as underlying sands are unwatered. After the storage in some locality has been depleted by withdrawals from wells, if there is slow drainage of inferior water from the finer-textured sediments, a cessation or reduction in rate of withdrawal from some wells would result in increasing salinity of water in those wells. In the area northeast of Teboulba, where several wells have been abandoned because of the salinity of the water, this salinity may have resulted from contributions of inferior water from the silts and clays in the dewatered sediments. A detailed history of operations will be sought in this area, where several wells contained saline water by 1940.

Underlying sediments – The system of ground-water development at Teboulba — by digging of wells a few meters into the zone saturated at the time of digging — provides no information concerning the fresh-water reserves or the underlying saline waters that might be hazards to present or future development. Available data from the developed zone (down to 75 m depth) do not indicate any substantial increase of salinity in water from wells that have been used for 20 years or more, although several of those wells have been deepened considerably since 1940. The water from the deepest wells is of comparable quality to that in wells that reach depths of only 40 to 50 meters.

6. PROGRAM OF TEST DRILLING

Many questions concerning the hydrology of the Teboulba region could not be answered by data from existing wells and development: the depth to which the sediments are saturated with usable water; hydrologic characteristics of the deeper aquifers and the quality of water in them; the existing and potential contamination by water from the sea, the Sebkha, or saline aquifers. For this information a test-drilling program was begun in February 1961.

The first test hole is about 1 km. west of Teboulba and adjacent to the municipal Chateau d'eau, which obtains water from a well 44 meters deep. There are 50 wells within 500 m of this test hole, of which 19 are equipped with motor-driven pumps. Thus, the test hole is in an area of heavy withdrawal, where water is of good quality. The test hole had a total depth of 282 m. It penetrated lime hardpan to a depth of 12m, and two other thin layers of lime hardpan between 25 and 35 m. From the water table (at 40 m) to a depth of 95 m., the sediments are prevailingly sandy silt and clay, but include six beds of sand with total thickness of 16 m; the waters in these sands were estimated to contain 1,700 to 2,400 ppm of dissolved solids. Three additional beds of fine sand totalling 21 m were logged between 123 and 159 m, with dissolved solids estimated to range from 3,000 to 4,400 ppm. The water in all sands below the depth of 160 m, was saline and unusable (slide 15).

The second test hole was placed about 400 m from the Mediterranean shore and north of the depression created by pumping. The nearest well yields water with about 3,000 ppm of dissolved solids, but others nearer to the sea have highly saline water. The purpose of this test well is to determine the relations of saline to fresh water at depth. A third test hole is planned in the vicinity of the brackish ground-water ridge east of Ksar Hellal. The sites for other test holes will depend partly upon the information obtained from these first three holes.

7. PRESENT CONCEPTS

As this paper is being written, studies of the Tebouilba area are still in progress and the program of test drilling has hardly begun. The following concepts are therefore tentative and subject to some modification in detail.

1. The shallow ground-water body contains usable water down to depths of more than 100 meters below sea level. The permeability of the sediments and the quality of the water in them vary laterally and vertically. Commonly the most permeable beds (find sand) contain water with 500 to 2,000 ppm of dissolved solids, but the finer-textured sediments may contain water far more mineralized.

2. At present the extent or continuity of individual sand beds or of the less permeable beds which act as confining layers between these aquifers is not known.

The method of development of any wells ordinarily explores only one saturated aquifer at a time, but in many of the deeper wells there is leakage and dripping from sand beds several meters above the bottom. In some areas marked differences in static levels in adjacent wells indicate separate and distinct aquifers, and they may indicate also a lenticularity and discontinuity of aquifers.

3. Natural replenishment of this reservoir is by precipitation upon the area, with downward movement through sandy or silty soils, "croûte calcaire", and underlying sediments. Because of the arid climate and the relative impermeability of many of the soils and underlying materials, the average rate of replenishment is low. In some places the water reaching the aquifer is fairly fresh; in others it is mineralized during transit downward from the surface, so that the shallowest water is more mineralized than that at greater depth.

4. Withdrawals from wells have long been in excess of the average rate of replenishment, and the rate of withdrawal is increasing. Much water has been removed from storage, and the upper limit of the saturated zone — presumably above sea level throughout the area under natural conditions (2000 years ago) — is now below sea level under most of the area.

5. Present conditions are favorable for inflow of inferior water to the reservoir, including sea water and water from the Sebkha, but such intrusion is not known to have progressed inland as much as half a kilometer at any point. Inferior water may also drain from finer-textured materials as water is withdrawn by wells from contiguous sand beds, and this may occur in all parts of the reservoir.

6. Because of the slow rate of inflow of inferior water from overlying strata as well as from sea and Sebkha, the optimum use of water is logically achieved by continuing to deplete the storage in the reservoir at such a rate as to obtain a blend with the inflowing water that will be usable for irrigation. This will certainly require continuing withdrawals of water at rates greater than the limited natural replenishment from precipitation. In other words, water balance cannot be maintained if the reservoir is to be utilized to best advantage.

7. The first test hole in the area indicates a decreasing proportion of permeable sediments with depth, and an increasing mineralization of the contained water. Water more than 160 m. deep is too saline for use. By exploiting the zones down to 160 m now, pumping the water and blending it with the water from shallower zones, the total yield of usable water from the reservoir may be increased, although the blended water will be inferior to that now obtained from the shallow zone alone.

8. The estimation of the total volume of usable water in storage, the present and potential rates of depletion, and the probable duration of yield from the reservoir, must await further data. Clearly an irrigation economy in the Teboulba region cannot be sustained permanently by the local ground-water resources, and eventually water must be imported from other regions or irrigation must cease. However, the local resources can sustain an irrigation economy for several years, or even decades, at less cost than must be paid for imported water.

LITERATURE CITED

Cointepas, J.P., 1959, Les sols de la zone cotière entre Sidi Bou Ali et Mahdia: Groupe HAR Section spéciale d'Etudes de Pédologie et d'Hydrologie, 23 p., 7 annexes.

ÉTUDE DÉTAILLÉE DU DÉVELOPPEMENT DE RÉGIONS

DETAILED STUDY OF THE DEVELOPMENT OF REGIONS

THE EXPLORATION AND DEVELOPMENT OF GROUND-WATER RESOURCES IN IRAN.

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ABSTRACT

An engineering approach to the exploration and development of groundwater resources has proved highly successful in Iran. Geohydrologic reconnaissances followed by engineered well construction and development, and by controlled pumping tests at 17 sites have led to the completion of 40 production wells with an average yield of 400 gpm.

At the Tehran Depot site, approximately 140 ft of saturated alluvial sand and gravel was tapped by two wells, each of which can produce in excess of 1,000 gpm. The data obtained during the drilling, sampling, screening, developing, and testing of these two wells is presented in considerable detail.

Evaluation of such empirical data and its subsequent publication is felt to be a major contribution to the science of ground-water hydrology in light of the fact that most of the available quantitative studies are limited by a variety of unknown quantities that usually defy adequate determination.

Application of engineering principles to water well completion and evaluation is one answer to the immediate problem of obtaining ground-water supplies in arid zones.

RÉSUMÉ

Un essai technique d'exploration et de développement de ressources en eaux souterraines s'est révélée une belle réussite en Iran. Une reconnaissance géohydrologique suivie par la construction de puits et par des essais contrôlés de pompages à 17 endroits ont conduit à la réalisation d'un ensemble de 40 puits producteurs avec un débit moyen de 400 gpm.

Au sité dénommé Téhéran Dépot, une nappe de 140 pieds d'épaisseur dans le sable et le graveir, deux puits donnent chacun plus de 1000 gpm. Les faits relevés pendant le fonçage, l'échantillonage, la mise en place des parois perforées, le developpement et l'essai de ces deux puits sont présentés en détail.

1. INDRODUCTION

Pertinent hydrologic papers in the current literature appear to fall into one of two classes: carefully reasoned and usually complex solutions for some specific and limited case; or broad quasi-mathematical statements containing unknown factors precluding an accurate quantitative evaluation of the general case.

Often overlooked in this forest of scientific literature is the root of such studies — the immediate and beneficial development of ground-water supplies.

In Iran the problem is not a lack of ground water but rather a lack of engineered well construction to develop water, and the consequent accumulation and subsequent presentation of data and findings.

In July 1959, The Frank E. Basil Company, Inc., embarked upon a program for the U.S. Army Corps of Engineers for the exploration and development of ground-water resources in Iran. To date the results have been eminently successful. At 17 sites along the western and northern areas of the country, a total of 40 production wells have been completed. The yields of these wells range from 15 gpm to 1,500 gpm, and average 400 gpm.

This paper outlines the scientific and engineering approach used in the drilling, sampling, screening, developing, and testing of two wells at one of the sites, and the analysis and evaluation of the geohydrologic data obtained. This paper shows what can be done in arid zones to provide water and empirically add to scientific knowledge.

2. Description of the area

2.1. *Location*

The Tehran Depot site is located 7 1/2 miles west of the capital city of Tehran (see Fig. 1) and lies roughly at latitude 35° 40′ N. and longitude 51° 10′ E.

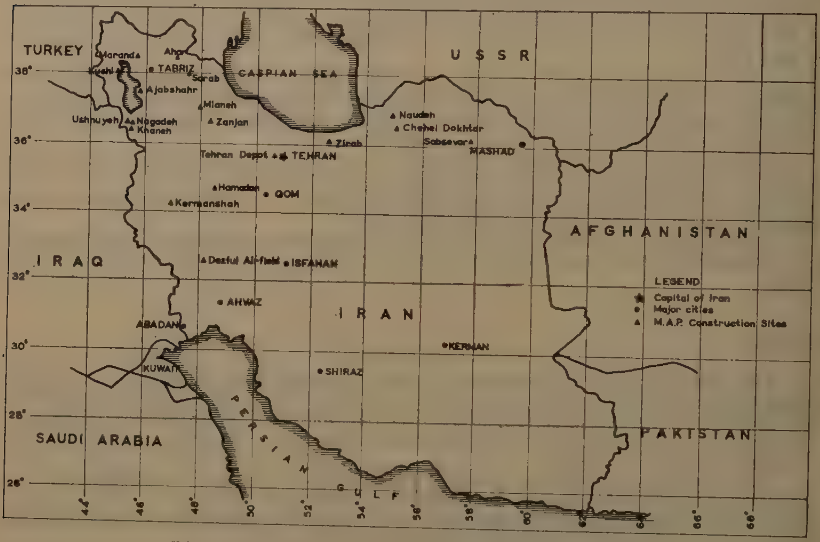

Fig. 1 — Map of Iran showing site locations.

2.2. *Previous Work*

In June 1957 Yost, assisted by Sarakissian, made a brief reconnaissance water-supply investigation of the site and reported his findings and recommendations to Gulf District, Tehran(¹). Earlier, in 1953, Rieben had made a study of the water resources of the Tehran area(²). Geologic data from both these reports are included herein.

2.3. *Climate*

Meteological data for the site(³) show that the average humidity is low, ranging in the winter from a minimum of 35 per cent to a maximum of 50 per cent, and in the summer from 25 to 35 per cent. In winter the average temperature ranges from a low of 28° F to a high of 77° F, and in the summer from 48° F to 97° F. The average annual rainfall totals about 8 inches.

2.4. *Topography and Drainage*

Tehran Depot is located on an alluvial plain which slopes southward at approximately 180 feet per mile. The plain is bordered on the north by the northwest-southeast trending Alborz Mountains. Peaks of these mountains rise to altitudes of 18,375 feet above mean sea level whereas the altitude at the site is approximately 3,700 feet. Surface drainage, when it occurs, is channeled by many small, normally dry streams which flow in a generally southward direction. About five miles west of the site is the normally dry, southeastward trending Karaj River.

Physiographically, the deposits of this piedmont-type environment form the well-known alluvial cones and fans. These deposits are largely made by streams, and their surfaces slope away from the streams of deposition. As the deposits are composed of more or less porous materials, much water is lost by absorption as the intermittent drainage progresses across them; thus such streams disappear and deposit their entire suspended and tractional loads.

2.5. *Culture*

Tehran Depot lies only 7 1/2 miles west of the city of Tehran which in 1958 had a population of about 1,500,000. The estimated population in 1960 of the Greater Tehran area was 2,200,000. The site is located immediately south of the old Tehran-Karaj highway and adjacent to and north of the Tehran-Tabriz railroad. Between the city limits and the site new industrial sites are being developed, and the demand for ground waters is increasing accordingly. Yost(1) gave data on several wells that in 1957 were yielding from 200 to 810 gpm from the alluvium at depths ranging from about 340 to almost 600 feet. These wells are upgradient from Tehran Depot but at distances ranging up to five miles and thus will have no short-term or longterm effects upon the wells at Tehran Depot. Likewise, ghanats adjacent to the site, which supply small amounts of water for irrigation purposes, will not affect the depot water supply. In his resume of well data, however, Yost(1) reported that many of the deeper wells inventoried (500 feet or more) had water of poor quality (i.e. saline in varying degrees), but that the shallower wells had water of good quality.

3. GEOLOGY AND HYDROLOGY

The consolidated volcanic bedrocks underlying Tehran Depot are unconformably overlain by an estimated 600 feet of Quaternary and an estimated 1,400 feet of Tertiary alluvial deposits(1). These surficial deposits are composed of lenticular beds of gravel, sand, silt, and clay which are largely semi-consolidated as shown by the fact that wells and ghanats require no casing to hold up the formation. Sorting and stratification are generally poor, or at least very imperfect. The lenses persist for but short distances; thus, lithologically, the deposits vary considerably in both vertical and horizontal directions. Inasmuch as the upper Bakhtiary formation of Tertiary (Pliocene) Age, and the underlying Fars facies (Pliocene) contain some gypsum and traces of salt(2), it is implied that during this period of deposition basins formed that were deep enough to contain water in which clays, silts, lime carbonates and evaporites were deposited. Rieben(2) reports that the boundary between the sediments of Quaternary Age and Tertiary Age is marked by a whitish clayey crust at the upper surface of the older alluvium, plus a reddish clayey-earthy deposit at the base of the younger Quaternary. Thus, a well that penetrates this marker boundary may encounter saline waters and drilling to such depths should be avoided.

Ground water in the surficial sediments underlying Tehran Depot occurs under water table or unconfined conditions, although locally artesian or confined conditions caused by clay lenses may exist. The ground water is derived entirely from precipitation. Roughly, one inch of rainfall over an area of one square mile provides about 17 million gallons of water. Assuming an average annual precipitation of about 8 inches and a land area of influence of about 40 square miles, the total precipitation upon the area presumably affecting Tehran Depot provides about 5 billion gallons per year. Part of this water flows off rapidly on the steep mountain slopes but subsequently is largely absorbed by the lower alluvial deposits and becomes ground water, part is evaporated directly, part is transpired by plants, and part sinks directly down to the zone of saturation to recharge the ground-water reservoirs. The water table slopes in a generally southward direction, and at the site the hydraulic gradient is 2.4×10^{-3} ft/ft (i.e. the elevation of water level in Well No. 1, which is 590 feet south of Well No.2, is 1.4 feet lower in elevation than that in Well No.2).

Admittedly, the above hydrologic description is sketchy, but it does suggest an order of magnitude for potential recharge. No attempt was made to make the desired ground-water inventory of the area because of various limitations. When the basic formula RECHARGE = DISCHARGE ± CHANGE IN STORAGE is expanded to include all revelant factors, it becomes evident that applicability is limited to cases were sufficient time and adequate funds are available to accumulate data on a) meteorology of the entire drainage basin, b) infiltration rates throughout the area, c) run-off, d) discharge from all wells and springs, e) discharge to all other formations by underflow, f) losses by evapotranspiration, g) natural changes in static water levels, and h) the hydraulic characteristics of the entire ground-water reservoir. In the arid zones of the world, rarely is the time or money available.

4. WELL CONSTRUCTION

4.1. Well No. 1

Operations at Well No. 1 commenced on 29 Aug 59 with the arrival of a Keystone No. 63 cable tool rig. The crew was composed of an American ground-water geologist, an American drilling superintendent, two Iranian drillers, and three Iranian laborers. A 14-inch hole was drilled, bailed, and sampled to a completion depth of 291 ft. Samples were collected every 5 ft. above the water table and every 2 1/2 ft below the water table which was encountered at 152 ft. The 12-inch steel casing followed the drilling in order to prevent caving of the hole and was set with bottom at 273 ft.

A rigid spindle 40 ft long with three 1-ft long rings was lowered into and raised out of the 12-inch I. D. casing. The rings were cylindrical and spaced one at each end of the spindle and one in the center. This test showed that the casing was set round, plumb, and true to line.

Twenty feet of nominal 12-inch (11 1/4" O. D.) Johnson stainless steel welded screen of slot size 60 (0.060") was installed with bottom set at 290.6 ft. The screen assembly had a closed bail bottom and a lead packer top which was swedged to seal the screen to the casing.

The well was surged for 12 hrs with a Johnson solid pump-valve surge plunger, and also developed for three days by air pumping and surging with a 600 cfm compressor. The air development pipes were raised and lowered several times daily the length of the 20 ft screen. Approximately 3 cu ft of fine sand and silt were developed through the well screen.

On 15 Nov 59 an oil-lubricated Worthington pump, with five bowls and 6-inch column was installed with the intake set at a depth of 196 ft. The well was developed through 16 Nov 59 by pumping and backwashing or surging. At 0830, 17 Nov 59, a 48-hour drawdown test was started, followed by a 24-hour recovery test commencing at 0830, 19 Nov 59. A total of 1,728,400 gallons of sand-free water was pumped during the 48-hour test at an average rate of 600 gpm. The rate of pumping and the total volume of water pumped were measured with a 4-inch Sparling Mainliner flowmeter.

Details of the aquifer tests, and of the subsequent 4-hour multiple step-drawdown test, are included in a following section.

4.2. Well No. 2

Operations at Well No. 2 commenced 10 Sep 59 with the arrival of a second Keystone No. 63 cable tool rig. Rigging up and hand-digging an 18-inch diameter hole to a depth of 20 ft. comprised the preliminary work. A 12 1/4-inch bit was used to start the actual drilling and an open-hole drilling technique (no casing) was employed inasmuch as the upper clayey formation was standing up and there was a negligible loss of drilling water. Drilling, bailing, and sampling continued to a depth of 203 ft. A 14 1/4-inch bit was then used to ream the hole in preparation for lowering the 12-inch casing. On 30 Sep 59 the bottom of the casing was at 194 feet. Open-hole drilling continued to a depth of 310 ft. and then the hole was reamed and the 12-inch casing lowered to a depth of 240 ft. Several minor cave-ins necessitated several tens of feet of redrilling but on 10 Oct 59 the bottom of the casing was at 292 ft. and on 11 Oct the hole was drilled and bailed to 315 ft. The rate of drilling as of this date was about 14 ft./day, including all delays.

The 20 ft of No. 80 slot Johnson screen was set with bottom at 312 ft., three feet having been backfilled in order to better seat the screen. Surging and pumping with compressed air at rates up to 100 gpm continued from 19 Oct 59 through 22 Oct 59, at which time the discharging water was free of sand. Upon removal of the discharge and air lines, approximately 1.5 cu ft of fine sand was bailed from the bottom of the screen.

Further development of the well was carried out by overpumping and backwashing with a 6-inch, 5-bowl Worthington pump. This phase of the development work was carried out until 31 Oct 59, and for a maximum pumping rate of 678 gpm, the maximum drawdown reached was roughly 9 ft.

A 48 1/2-hour drawdown test began at 0800, 7 Nov 59, and continued until 0830, 9 Nov 59, at which time a 24-hour recovery test commenced. A total of 1,739,400 gallons of sand-free water was pumped during the drawdown test, indicating an average pumping rate of 598 gpm. A 3 1/2-hour multiple stepdrawdown test was completed on 10 Nov 59. Details of these hydraulic tests are included in a following section.

Well No. 1 was 100 per cent complete on 21 Nov 59 and Well No. 2 was 100 per cent complete on 12 Nov 59.

5. DESCRIPTION OF MATERIALS PENETRATED

The alluvial deposits beneath Tehran Depot comprise materials ranging in size from clay to boulders. There follows below logs of materials penetrated by Wells Nos. 1 and 2.

Figure 2 is a graphical representation of Wells Nos. 1 and 2 and of the descriptive logs. The similarity of materials penetrated by both wells is readily apparent. In Figure 3, 12 mechanical analyses plotted as cumulative frequency curves illustrate the variability of grain sizes comprising the aquifer at Well No. 1 at depths between 156 and 290 ft., and at Well No. 2 at the depth of the well screen.

The results of mechanical analyses of well samples must be accepted with caution. The alluvial material is highly variable throughout, so a small sample is at best characteristic only of the sediment in its immediate vicinity. In addition, these are not undisturbed samples, having been collected from a well drilled with a cable tool rig. The evidence that these analyses present, therefore, is only suggestive. Thus, the average total porosity determined for the aquifer (33.2%) is regarded as a large porosity,

TABLE I

Well No. 1 descriptive log

Description	Thickness (feet)	Depth (feet)
Clay, gray with some angular gravel up to 3 inches	10	10
Clay, silty, gray with some gravel and few boulders	40	50
Clay, silty, gray, and sand	20	70
Clay, silty, gray with pebble gravel and an occasional boulder	29	99
Clay, silty, gray with gravel and fine to medium gray sand	41	140
Clay, silty, gray with cobble gravel and some very fine sand	10	150
Sand, fine to coarse, and pebble gravel	22	172
Sand, fine to coarse, pebble gravel, and little silty clay	16	188
Sand, fine to coarse, pebble gravel, and some silt	11	199
Sand, very fine to coarse, and pebble gravel	16	215
Sand, fine, silty, with clay, grading to coarse sand and gravel	22	237
Sand, fine to coarse, and gravel, with some clay	48	285
Sand, fine to coarse, and gravel, with very little clay	6	291
Bottom of hole at		291

Total number of samples: 96
Static water level : 155.08, 17 Nov 59
Screen : 20 ft of No. 60 slot with bottom at 290.6 ft
Casing : 12-inch with bottom at 273 ft

recognizing, however, that such data to not indicate the specific yield or effective porosity of the material. The 17.7 average uniformity coefficient (which is the ratio of the diameter of a grain that has 60 per cent by weight of the sample finer than itself to the diameter that has 10 per cent finer than itself) indicates a poor degree of uniformity of size. In a sand-gravel mixture such is to be expected. The effective grain size (which is the diameter of a grain of such size that 10 per cent of the sample by weight consists of smaller grains and 90 per cent of larger grains) averages 0.26 mm, indicating that most of the aquifer material is coarser than fine sand. The average of median grain size of 2.8 mm indicates that 50 per cent of the material is in the range of coarse sand.

In summation, the aquifer penetrated by Well No. 1, and, by correlation, by Well No. 2, consists chiefly of poorly sorted coarse granular material. Conclusions as to effective porosity, permeability, and well productivity cannot be made inasmuch as there is no way to evaluate quantitatively and accurately the effects of such features as packing, roundness, size, and shape of grains.

The gradation curves were used to assist in selecting a proper screen size for Well No. 1 and for Well No. 2. It is common practice to select a size opening somewhere between the 60% and 80% finer by weight size(4). However, a brief study of Figure 3 shows that such limits dictate about a 5 mm size, or a 0.20-inch opening (No. 200 slot). Development of a well using such a size screen would be a prohibitively lengthy procedure, and in light of the fact that the site requirement called for

TABLE 2

Well No. 2 descriptive log

Description	Thickness (feet)	Depth (feet)
Clay, gray with gravel to boulder size	35	35
Clay, silty, gray with pea gravel	10	45
Clay, silty, gray with fine sand and pea gravel	14	59
Clay, gray with pea gravel	41	100
Clay, silty, gray with pebble gravel	30	130
Clay, silty, gray and fine to coarse sand with gravel	23	153
Clay, gray and fine to coarse sand and gravel. Grading with depth to coarser sands and larger gravels	21	174
Sand, fine to coarse, and gravel to pebble size (3″)	19	193
Sand, fine to coarse, and semi-rounded gravels	10	203
Sand, fine to coarse, little silty clay	17	220
Sand, fine to coarse, and gravel, some silty clay	70	290
Sand, fine to coarse, medium gravel. Some «heaving»	25	315
Bottom of hole at	....	315

Total number of samples: 93
Static water level : 166.27 ft, 7 Nov 59
Screen : 20 ft of No. 80 slot with bottom at 312 ft
Casing : 12-inch with bottom at 292 ft

only 75 gpm, a screen opening of 0.06 inches (No. 60 slot) was chosen for Well No. 1 and 0.08 inches (No. 80 slot) was chosen for Well No. 2. A 12-inch, No. 60 slot screen permits the free entrance of 62 gpm per foot of screen without danger of plugging the screen with sand, and the capacity of a 12-inch, No. 80 slot screen is 75 gpm per screen foot(4). Complete development of each of these wells, each of which has 20 feet of screen, has resulted in well capacities far above minimum requirements.

6. Ground-water and well hydraulics

The withdrawal of water from any aquifer causes the water levels to decline in the vicinity of the point of withdrawal—the well. The overall size, shape, and rate of growth of the cone of depression are dependent on the rate and duration of pumping, the transmissibility and storage coefficients of the aquifer (*), the increase, if any, in recharge induced by the declining water levels, the natural discharge that

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(*) The coefficient of transmissibility, *T*, is expressed as the rate of flow of water, at the prevailing water temperature, in gallons per day, through a vertical strip of the aquifer 1 foot wide extending the full saturated height of the aquifer under an hydraulic gradient of a 1 foot drop in head in 1 foot of flow distance.

The coefficient of storage, *S*, of an aquifer is defined as the volume of water it releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. For water-table aquifers it is considered equal to the specific yield or effective porosity.

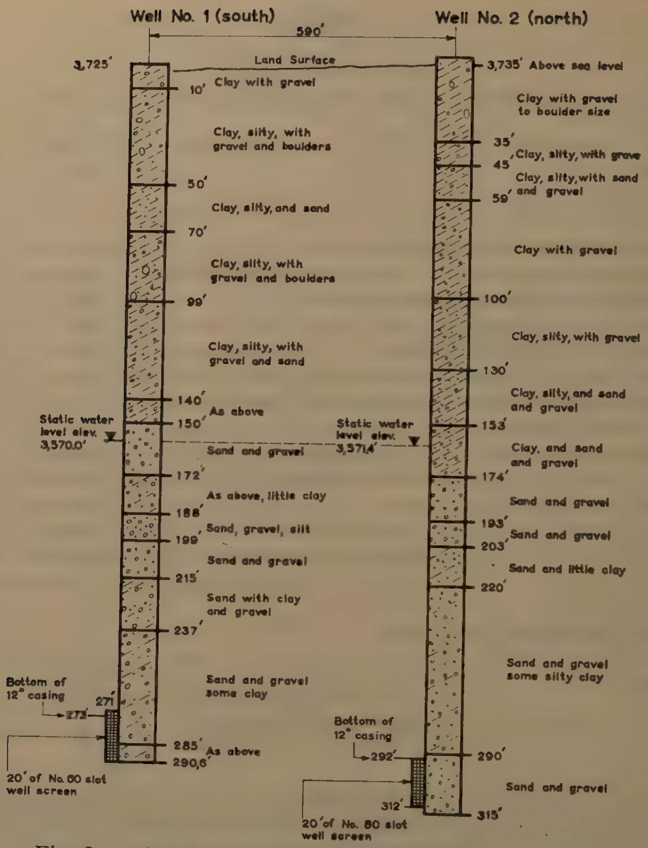


Fig. 2 — Graphical representation of Well Nos. 1 and 2.

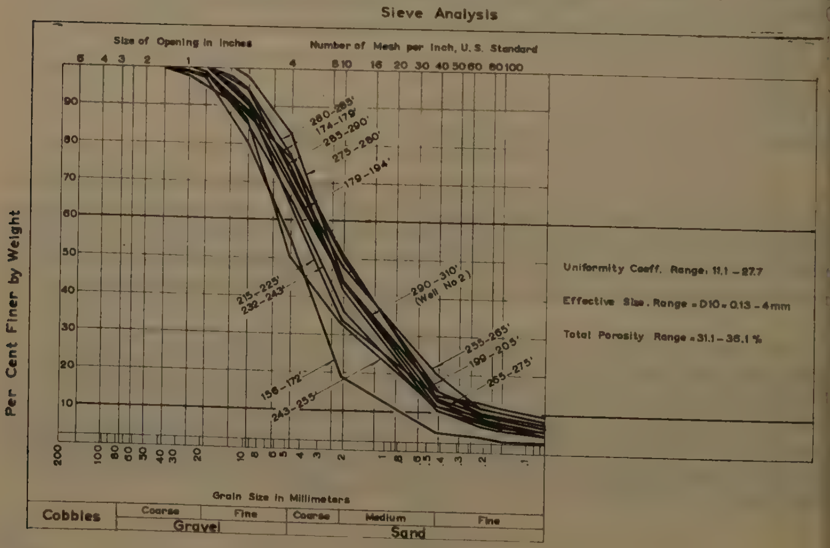


Fig. 3 — Gradation curves.

is captured, and the hydrogeologic boundaries of the formation. The lowering of the water level is dependent on the variables mentioned above and on the distance from the point of withdrawal.

Equations have been developed expressing the relation among the variables that govern the magnitude of the unwatering effects, and methods have been developed for graphically analyzing these equations(5)(6). The data obtained during the hydraulic tests on both Well No. 1 and Well No. 2 have been analyzed by several of these methods chosen as being the most appropriate for the prevailing conditions. Inasmuch as ground-water hydraulics is a rapidly developing science, and one which is often misunderstood or ineptly applied, it is felt that a discussion here of some important principles is justified and appropriate.

6.1. *Aquifer Tests*

6.1.1. *Well No. 1*

The aquifer test data collected during the drawdown-recovery test on Well No. 1 are plotted on Figure 4 which is the hydrograph for the well and which also graphically defines the time-drawdown-recovery terms used herein.

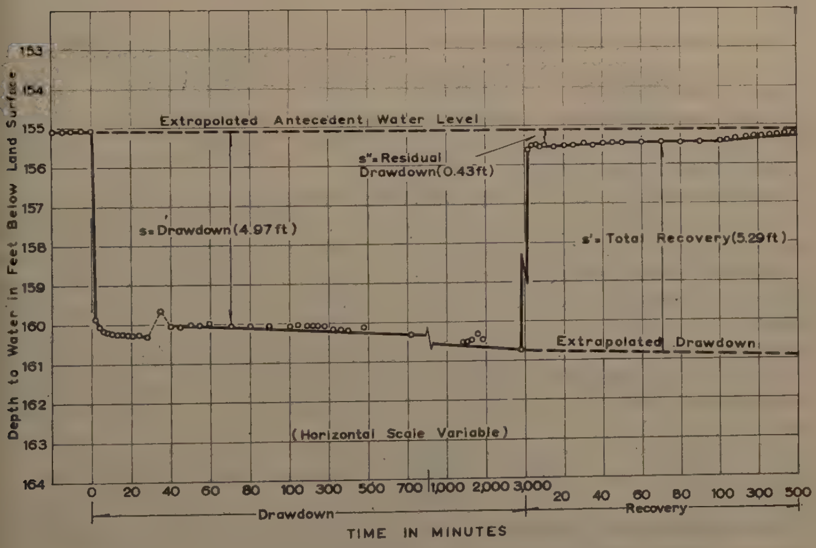


Fig. 4 — Drawdown—recovery hydrograph, Well No. 1 test.

Figure 5 includes two different time-recovery curves. It has been shown(7) that when plotted on semi-logarithmic paper, the theoretical drawdown curve approaches a straight line where sufficient time (t) has elapsed after pumping started. From the portion of the data which plots as a straight line, the transmissibility of the aquifer may be determined by use of the following equation:

$$T = \frac{264\,Q}{\Delta s} \tag{I}$$

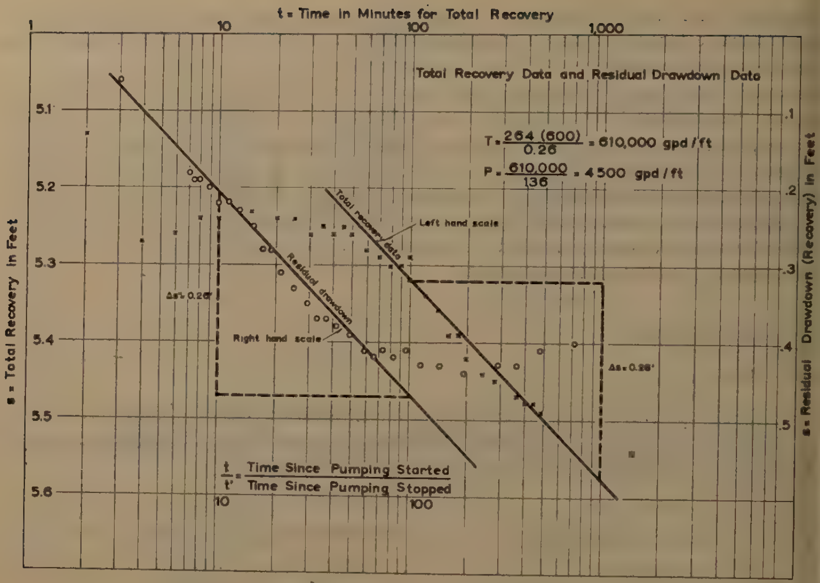


Fig. 5 — Time—recovery curves for Well No. 1.

where T is the coefficient of transmissibility in gpd/ft, Q is the discharge rate of the well in gpm and Δs is the change in drawdown in feet per log cycle in the straight-line portion of the drawdown curve.

This equation can be used also with data showing the recovery of water levels after pumping stops. In such a computation, s' is the total recovery in feet and the time t' is plotted since pumping stopped. Recovery data have a decided advantage in that they are not affected by erratic pumping rates. (Maintaining a constant pumping rate by throttling the engine is often a difficult operation.) The pumping rate varied ± 3% during the test on Well No. 1 and the drawdown curve of Figure 4 shows the effect of these variations. However, the curve showing total recovery data on Figure 5 shows that after sufficient time (about 1 hour) had elapsed, the plotted points approximated a straight line and the coefficient of transmissibility was calculated to be

$$T = \frac{264\,Q}{\Delta s'} = \frac{264\ (600)}{0.26} = 610{,}000 \text{ gpd/ft}$$

The effective saturated thickness of the aquifer, m, is 136 feet at Well No. 1, thus the coefficient of permeability, P, is calculated to be

$$P = \frac{T}{m} = \frac{610{,}000 \text{ gpd/ft}}{136 \text{ ft}} = 4{,}500 \text{ gpd/ft}^2$$

where P is defined as the capacity of an aquifer for transmitting water, commonly expressed as the rate of flow of water in gallons per day through a cross-sectional area of 1 square foot under an hydraulic gradient of 1 foot per foot.

T was also determined by two other analytical methods. Thus, the plotted points in Figure 5 showing residual drawdown are based on the equation

$$T = \frac{264\,Q}{s''} \log_{10} t/t' \qquad \text{(II)}$$

where s'' is the residual drawdown at any time during the recovery period (the difference between the observed water level and the non-pumping water level extrapolated from the observed trend prior to the pumping period), t is the time since pumping started, and t' is the time since pumping stopped. The analysis proceeds in much the same manner as for Equation I.

Figure 6 shows the observed recovery of water levels after pumping stopped. Inasmuch as this curve does not reflect the total recovery and because the aquifer was not in absolute equilibrium when pumping stopped, the calculated transmissibility (630,000 gpd/ft) is slightly higher than that obtained from the analyses of Figure 5. The three analyses, however, have given remarkably similar results considering the small order of magnitude of the rate of drawdown or recovery.

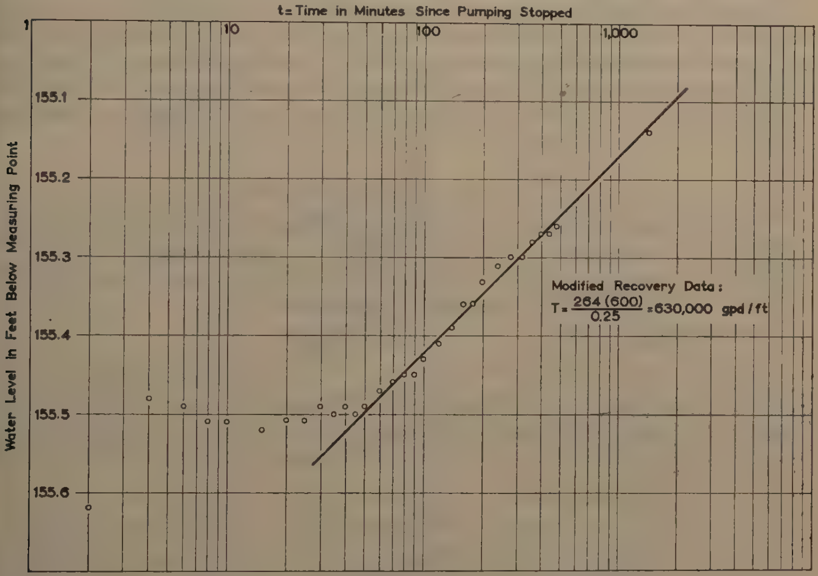


Fig. 6 — Recovery of water level in Well No. 1.

Knowing the aquifer coefficients permits prediction of the hydraulic behavior of the aquifer and such values are consequently used to solve many practical problems of ground-water flow, including the prediction of water levels, the design of well fields, and the determination of optimum well yields, all under stated conditions.

Beneath Tehran Depot ground water is flowing in a general southward direction at an average rate of about 14 ft/day; calculated thus:

$$v = \frac{PI}{7.48\,p} = \frac{4{,}500(2.4 \times 10^{-3})}{7.48\,(0.10)} = 14 \text{ ft/day}$$

Where v is the average velocity in ft/day, P is the permeability in gpd/ft^2, I is the hydraulic gradient in ft/ft, and p is the effective porosity (conservatively estimated here to be 10%).

The total volume of flow moving southward through the tested aquifer is calculated as

$$Q = TIW = 610{,}000\ (2.4 \times 10^{-3})\ (6{,}560) = 9.6 \text{ mgd}$$

Where Q is the discharge in millions of gallons per day, T is the transmissibility in gpd/ft, I is the hydraulic gradient in ft/ft, and W is the width in feet of the aquifer beneath the long dimension of the site. The underflow amounts to more than 6,600 gpm.

Theoretical water levels at various distances from the well at various times and rates of pumping may also be calculated. The methods for such calculations need not be included here; suffice to say that they are based on assumptions from which Equations I and II were derived and that they are standard techniques extensively treated in the ground-water literature (8)(9)(10). Figures 7 and 8 show, respectively, time-drawdown graphs and distance-drawdown graphs which give the theoretical drawdown in water level at any distance from 1 to 10,000 feet from the well while discharging at 75, 110, 600, 2,000, or 4,000 gpm for any time from 1 to 10,000 days. It is assumed that no recharge occurs.

Figure 7 shows that at the site requirement of 75 gpm there will be only a 0.4 foot drawdown 1 foot from the pumped well after 10 years (3,650 days). Pumping 600 gpm for 10 years will produce a drawdown of about 2.7 feet at a distance of 1 foot and about 1.8 feet at a distance of 100 feet. Pumping 2,000 gpm for 10 years will produce a drawdown of about 9.3 feet at a distance of 1 foot and about 6.0 feet at a distance of 100 feet.

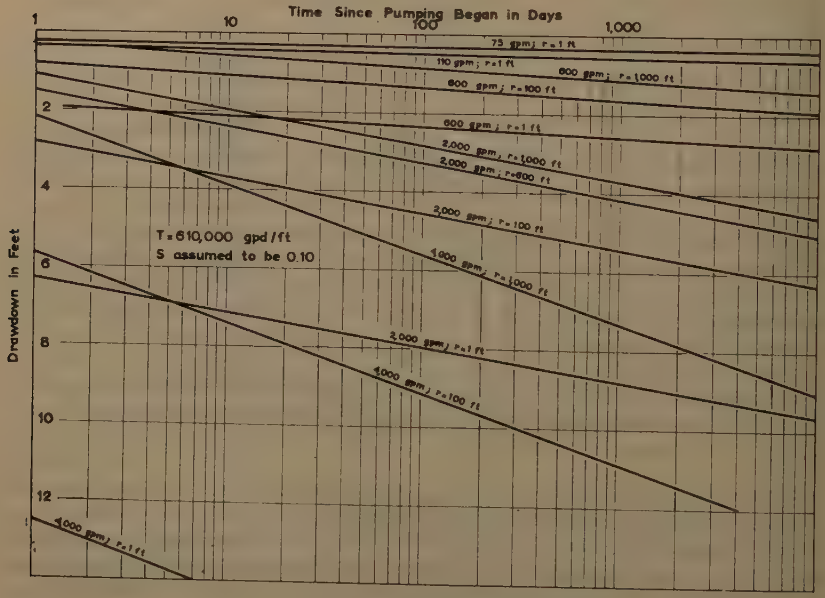


Fig. 7 — Time—drawdown graphs.

Figure 8 shows that after pumping 1 day at 75 gpm, there is a theoretical drawdown of 0.04 foot at a distance of 600 feet from the pumped well; at 600 gpm it is about 0.45 foot; at 2,000 gpm about 1.5 feet; and at 4,000 gpm about 3.0 feet. Consequently, interference with Well No. 2 will be negligible at all but the highest rates of discharge. Furthermore, theoretically, the aquifer is capable of easily sustaining a withdrawal of 4,000 gpm (5.8 mgd). This is indicated by the fact that after 10 years there will be a drawdown of only 19 feet at a distance of 1 foot from the point of withdrawal. Obviously, the drawdown at greater distances will be much less.

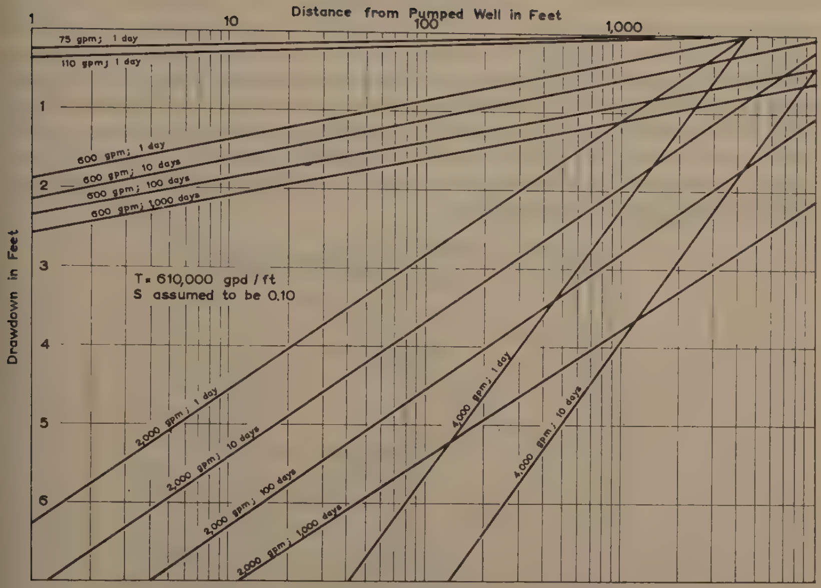


Fig. 8 — Distance—drawdown graphs.

6.1.2. *Well No. 2*

The field test data for the aquifer test at Well No. 2 are plotted on Figure 9 as a hydrograph showing the drawdown and recovery of water level during the test. Figure 10 includes semi-logarithmic plots of time *vs.* drawdown and time *vs.* total recovery.

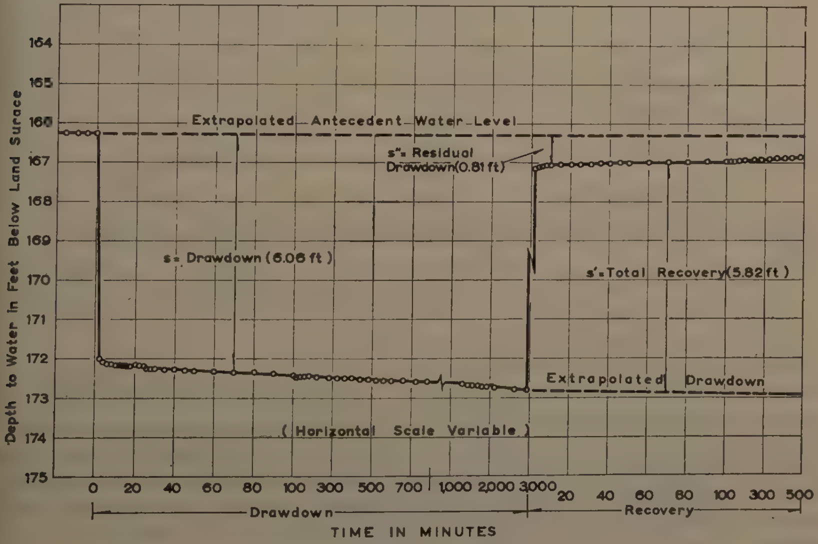


Fig. 9 — Drawdown—recovery hydrograph, Well No. 2 test.

Theoretically, the drawdown curve and the recovery curve should coincide. This would have occurred if the pumping rate had remained exactly constant throughout the pumping period of the test, if the aquifer had been in exact hydraulic equilibrium before pumping began, and if all the various assumptions on which the analytical equations are based were exactly true for this particular test. However, these conditions are rarely completely met in the field, and the recovery will usually depart slightly from the drawdown curve. The departure in Figure 10 amounts to only 0.25 feet. Figure 11 shows the time-recovery curve based on Equation II. Analyses of the data plots in Figures 10 and 11 indicate that

$$T = \frac{264\,Q}{\Delta s} = \frac{264\,(598)}{0.24} = 660{,}000 \text{ gpd/ft}$$

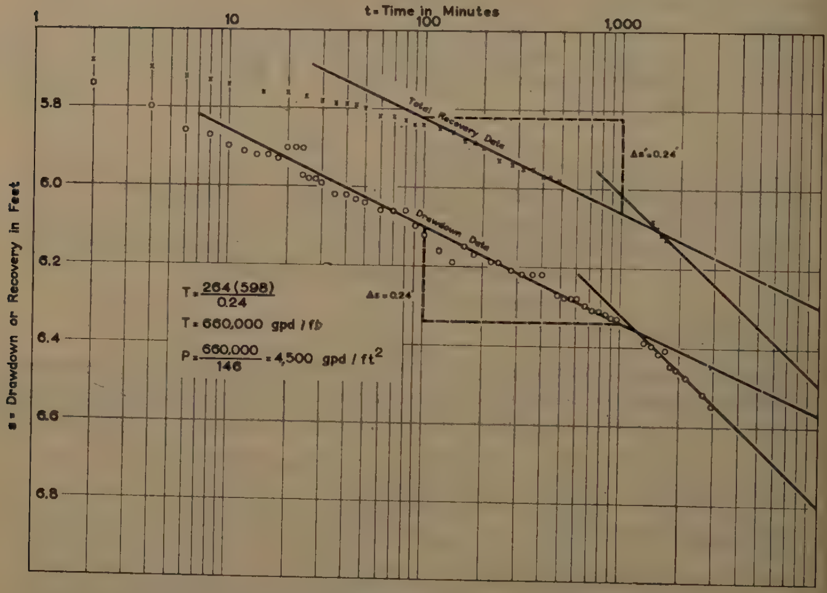


Fig. 10 — Time—drawdown (recovery) curves for Well No. 2.

The effective saturated thickness of the aquifer at Well No. 2 is 146 feet, hence

$$P = \frac{T}{m} = \frac{660{,}000}{146} = 4{,}500 \text{ gpd/ft}^2$$

This value is identical with that obtained at Well No. 1.

It is of importance to note that after about one day of pumping, the observed drawdown and recovery readings depart from the straight-line approximation. This is interpreted as being caused by a hydrogeologic boundary. Under boundary conditions, the water level initially recedes as expected as a cone of depression about the pumped well and the plotted field data curve downward and approach the straight line «first limb» of the curve as previously discussed. If, after continuing down this straight line they start to bend downward again and approach a straight line of a «second limb», it is because the cone of depression is being reflected back to the

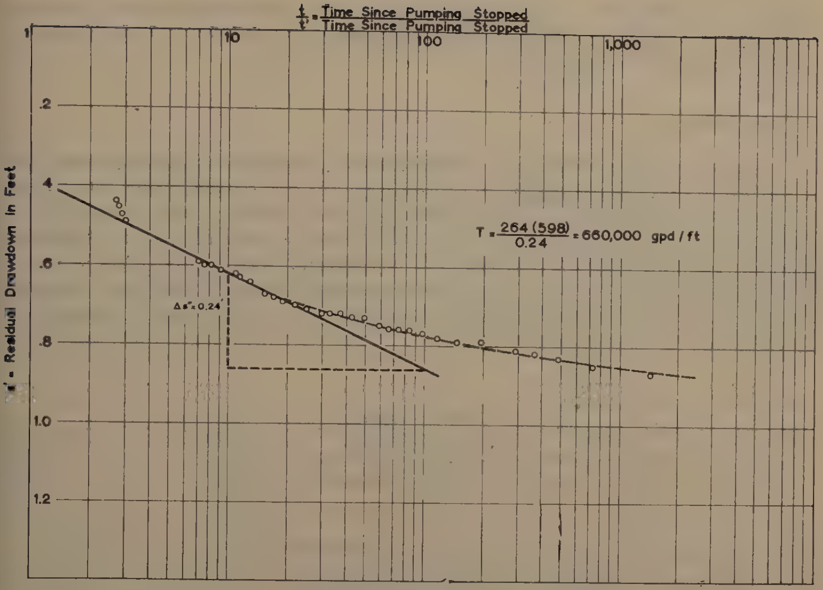


Fig. 11 — Time—recovery curve for well nº 2.

observation well from a boundary. The effect is the same as that caused by the imaginary cone of depression from an «image well» reaching the observation well. It should be noted that the Δs (change in drawdown per log cycle) is exactly twice as large for the second limb as it is for the first limb. This is the case because the image well is conceived to be pumping at the same rate as the pumped well.

If three or more observation wells had been available, it would have been possible to locate the image well and consequently the boundary by application of appropriate equations and computing methods. As it is, however, all that can definitely be stated is that a hydrogeologic boundary had been intercepted by the cone of depression of Well No. 2. Inasmuch as the test at Well No. 1 did not reflect this boundary, it can be assumed that it lies generally northward of the site and is probably caused by a thinning of the aquifer due to a greater thickness of impermeable clays and silts. Figure 10 shows that after about 7 days of pumping (10,000 minutes) the drawdown would be only 6.8 feet, or about 0.23 foot more than that if no boundary were present.

The value of the coefficient of transmissibility obtained at Well No. 2 agrees closely with that obtained at Well No. 1. Consequently, the calculations of flow rate and volume and the predictions of future water levels as given previously for Well No. 1 are to be considered appropriate for the site as a whole. They are on the conservative side.

6.2. *Step-Drawdown Tests*

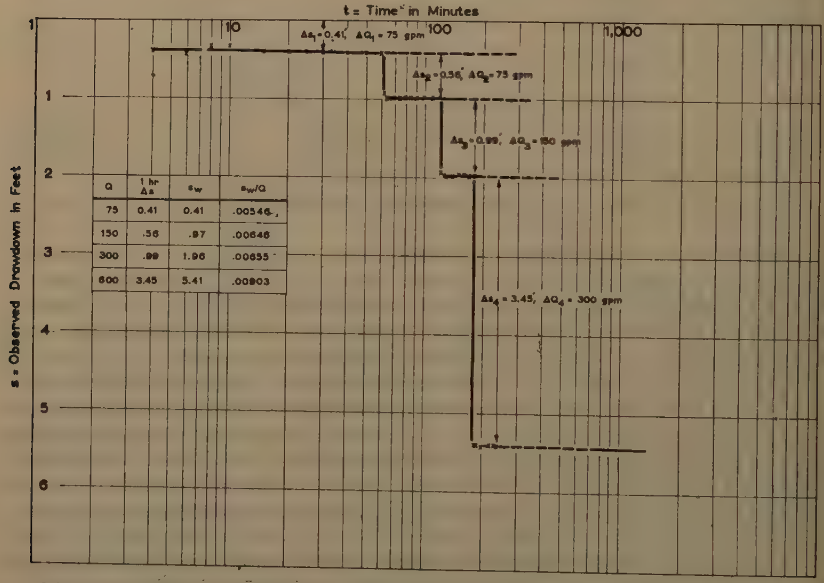
The drawdown in a well resulting from the withdrawal of water is made up of (*a*) head loss resulting from laminar flow in the formation (aquifer), and (*b*) head loss resulting from turbulent flow in the zone outside the well, through the screen openings, and in the well casing. These head losses may be evaluated using the equation (7)

$$s_w = BQ + CQ^2 \qquad \text{(III)}$$

where s_w is the drawdown in the pumped well, B is the «formation-loss» constant or the «resistance» of the formation, C is the «well-loss» constant or the resistance of the well, and Q is the discharge.

6.2.1. *Well No. 1*

Figure 12 is a plot of the data obtained during the multiple step-drawdown test on Well No. 1 and gives the step-drawdown calculations in tabular form. The values s_w/Q and Q are then plotted on arithmetic coordinate paper as shown in Figure 13. From the least squares linear estimation line for the plotted points, the following equation was determined: $s_w = 0.0052Q + 0.0000062Q^2$, which is the form of Equation III and is the approximate equation for the drawdown in Well No. 1 for the stated pumping period. Figure 14 shows a plot of this equation and the theoretical drawdowns for various pumping rates.



Q	1 hr Δs	s_w	s_w/Q
75	0.41	0.41	.00546
150	.56	.97	.00646
300	.99	1.96	.00655
600	3.45	5.41	.00903

Fig. 12 — Time—drawdown curves, step—drawdown test, for Well No. 1.

A well-efficiency curve is shown in Figure 15. For this plotting «well-efficiency» is defined as the ratio of the theoretical drawdown computed by assuming no turbulence is present, or approximately BQ, to the total drawdown in the well, or s_w. This curve shows a rapid drop in efficiency as discharge and hence turbulence is increased.

Well No. 1, as a structure, cannot sustain a pumping rate of 4,000 gpm although, as previously mentioned, the aquifer can supply water at this rate. Whereas the drawdown at 4,000 gpm in the aquifer is only 20.80 feet, the total drawdown inside the well is 120 feet. With a non-pumping water level of 155 feet, plus the 120-foot drawdown, the pumping level at 4,000 gpm would be at 275 feet which is several feet below the top of the screen. This is an undesirable condition. In addition, the capacity of a

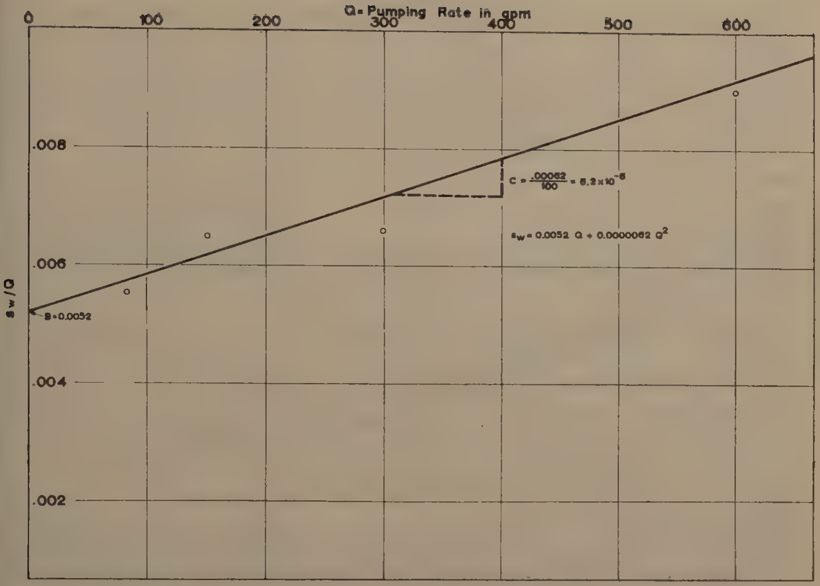


Fig. 13 — Plot of s_w vs. Q to solve for values of B & C, Well No. 1.

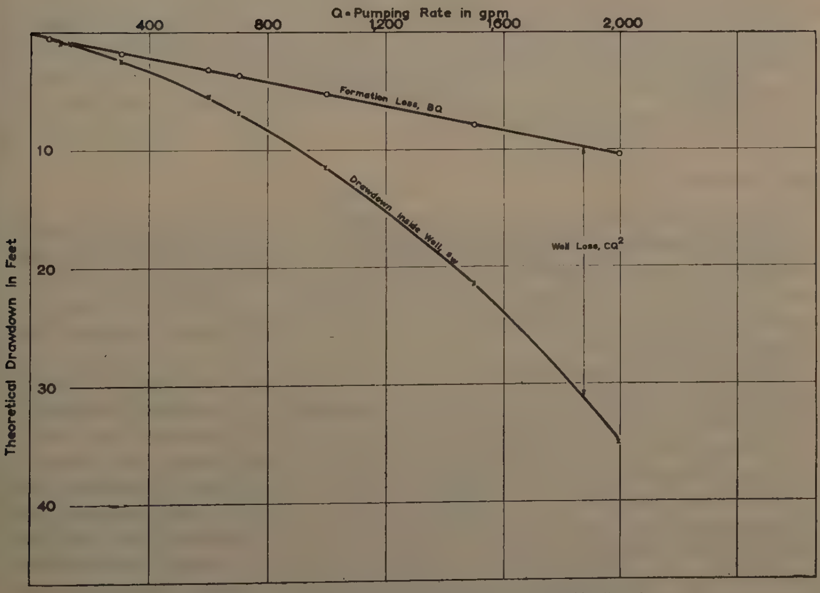


Fig. 14 — Drawdown—yield curve, Well No. 1.

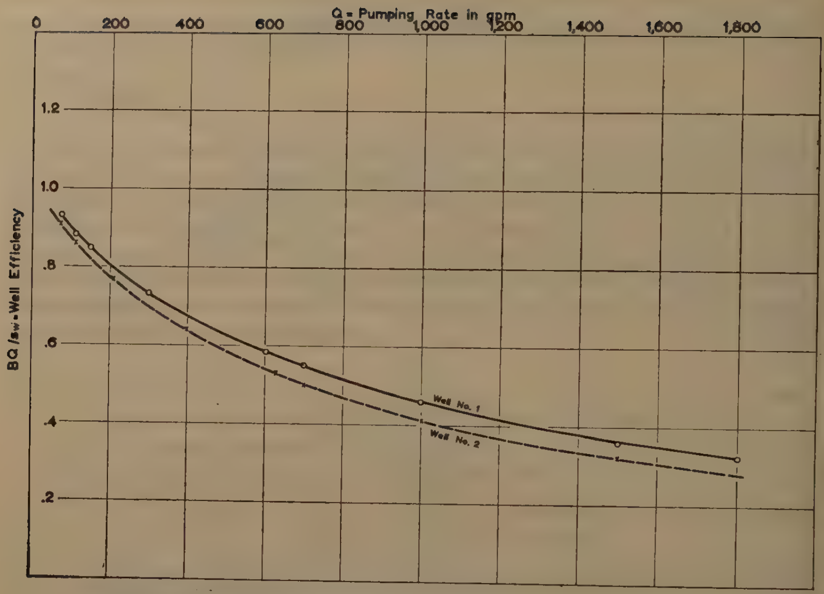


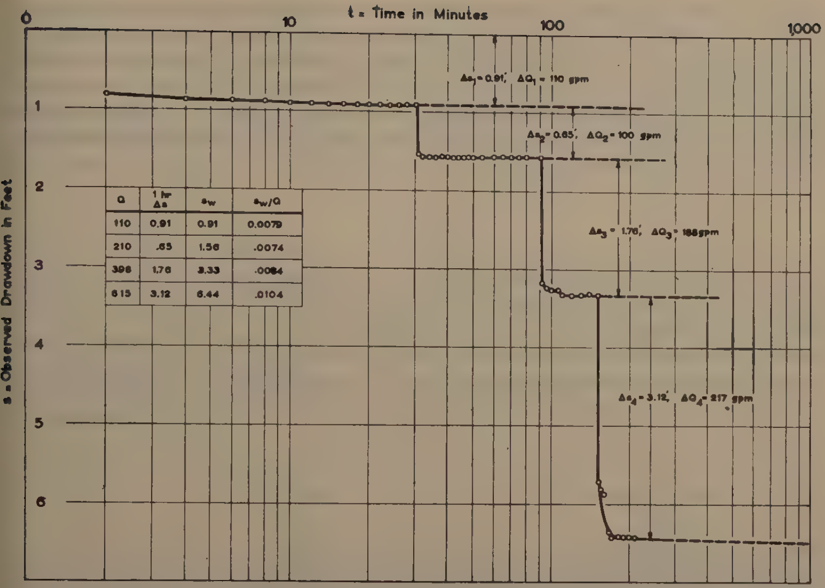
Fig. 15 — Graph showing efficiency of Well No. 1 and Well No. 2.

12-inch screen of slot size 60 is only 62 gpm/ft(4). Thus, the 20 feet of screen in Well No. 1 will permit free entrance of only 1,240 gpm without danger of eventually plugging the screen with sand. (There are 170 square inches of open area per foot of screen or 3,400 square inches of openings in this particular screen.) Well No. 1 may therefore be considered as being capable of sustaining a safe yield of about 1,200 gpm, with a drawdown calculated to be 15.2 ft.

6.2.2. *Well No. 2*

The 3 1/2-hour step-drawdown test on Well No. 2 was analyzed in similar fashion to the test on Well No. 1. Figure 16 is a plot of the field data and includes the step-drawdown calculations. The calculations were plotted and the equation for the drawdown in Well No. 2 was shown to be: $s_w = 0.0056Q + 0.000008Q^2$. In turn, this equation and the theoretical drawdowns for various pumping rates were plotted and are given in Figure 17.

The graphical procedures described above for both Wells Nos. 1 and 2 are considered best for treating problems based on measurements of physical quantities in which errors are inherent. However, the graphical method emphasizes the need for accurate data. Small errors in discharge or drawdown measurements will cause relatively large errors in B and C. Rounding or adjusting the original data graphically (as shown in the plots of s_w/Q *vs.* Q to solve for B and C) generally eliminates poor data; however, such a procedure must be done cautiously as adjusted data may lead to misinterpretation. The fact that the calculations for the drawdown-yield curve give theoretical drawdowns that agree closely with the observed drawdown at the four stepped rates of pumping, indicates that the graphical solutions given herein are



Q	1 hr Δs	s_w	s_w/Q
110	0.91	0.91	0.0079
210	.65	1.56	.0074
398	1.76	3.33	.0084
615	3.12	6.44	.0104

Fig. 16 — Time—drawdown curves, step—drawdown test, for Well No. 2.

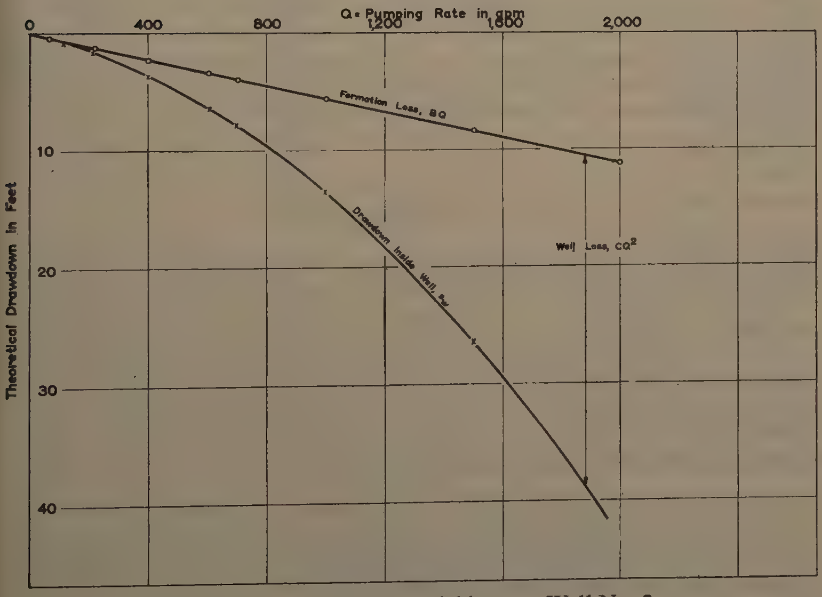


Fig. 17 — Drawdown—yield curve, Well No. 2.

quite reasonable. For example, at a pumping rate of 210 gpm, the observed drawdown in Well No. 2 was 1.56 ft. (Fig. 16) whereas the theoretical drawdown calculated from the equation for the well when pumping at 210 gpm is 1.53 ft., and at 615 gpm the observed drawdown was 6.44 ft whereas the theoretical drawdown was 6.48 ft.

The well-efficiency curve for Well No. 2 is shown in Figure 15 along with the curve for Well No. 1. It is readily apparent that Well No. 1 is the more efficient well, due probably to better development.

TABLE 3

CHEMICAL AND BACTERIOLOGICAL ANALYSES OF WATER FROM WELLS Nos. 1 AND 2

	Well No. 1	Well No. 2	U.S.P.H.S. Limits
Date of Sample Collection	17 Nov 59	8 Nov 59	——
pH	7.5	7.4	
Alkalinity (Phenolphthalein)	None	None	
Alkalinity (Menthyl-Orange)	135 ppm	125 ppm	ppm
Total Hardness ($CaCO_3$)	87.5	70	
Permanent Hardness (Non-carbonate)	37.5	15	
(HCO_3) Temporary Hardness	——	55	
Clorides (Cl)	15	15.5	250
Sulphates (SO_4)	24	14.4	250
Nitrates (N_2O_5)	5	6	
Nitrites (N_2O_3)	None	Trace	
Ammonia (NH_3)	None	None	
Calcium (Ca)	——	17	
Magnesium (Mg)	——	6.6	125
Iron (Fe)	——	None	0.3
Manganese (Mn)	——	None	
Organic Matter (Oxygen Consumed)	——	0.08	
Residue Dry (Total Solids)	242	237	500
No. of colibacillus germs per liter	None	None	
No. of germs/cc after 48 hours at 98.6° F (average of 5 bottles, control = 0)	26.4	186.2	
Temperature of Water (°F)	62	63	
Remarks by Pasteur Institute	«Good potable water»		

A brief study of Table 3 shows that the analytical results are well below the U.S.P.H.S. limits. The water is clear, pleasant to the taste, cool, neither corrosive nor scale-forming, free from minerals which would produce undesirable physiological effects, and free from organisms capable of producing intestinal infections.

Well No. 2, as with Well No. 1, cannot pump 4,000 gpm because of the excessive drawdown required at that rate. With a non-pumping water level of 166 ft., plus the calculated 150-feet drawdown at 4,000 gpm, the pumping level would theoretically be at 316 ft., an impossibility in the 312-ft. deep well. Inasmuch as the capacity of the 20-ft. long, 12-inch diameter, slot No. 80 screen is 1,500 gpm, the sustained safe yield of this well may be considered as being 1,500 gpm. The drawdown at 1,500 gpm is calculated to be 26.40 ft, and the pumping water level to then be roughly 193 ft.

7. Quality of ground water

In order to appraise the quality of ground water beneath Tehran Depot, samples of water were collected and chemical and bacteriological analyses made by the Pasteur Institute, Tehran. Table 3 includes the results of these analyses and lists the applicable limits for an acceptable water as given by the U.S. Public Health Service (4). A complete chemical analysis was made of the water sample from Well No. 2, and a partial analysis from Well No. 1.

8. Conclusions

The methods currently available for quantitative geohydrological studies are strictly limited in their applicability to the majority of field problems due to the various unknown quantities. However, the peoples and the places of the world in need of water cannot afford to wait for mathematical solutions to their problems. If ground water is available, if ground-water supplies can be developed by technically competent means, and if some consequent quantitative data can be added to the scientific literature, then progress has been achieved.

A program that includes a) a geologic and hydrologic reconnaissance of the area, b) a carefully supervised drilling operation which requires detailed sampling and recording of data, c) the selection of a proper well screen, d) extensive and complete development of the well, e) controlled aquifer and well performance tests, f) analysis and evaluation of hydraulic data, and g) the publication of the study for the permanent record, will go far toward satisfying both the ground-water users and the ground-water scientists.

REFERENCES CITED

(1) Yost, C.B., Jr. and Simon Sarakissian. *Water Supply Investigation, Ghom (Tehran Depot) Site 20*, Amman & Whitney-Husted, Architect-Engineers, New York, N.Y. 15 July 1957.

(2) Rieben, E.H. *Les Ressources en Eaux Souterraines de la Plaine Alluviale de Teheran*, United Nations Food & Agricultural Organization. August 1953.

(3) U.S. Army Corps of Engineers, Gulf District. *Data for the Orientation of Prospective Bidders, FY 1959 Construction Program*, U.S. Army Engineer District, Gulf, APO 205, New York, N.Y. 6 October 1958.

(4) U.S. Army Engineer Division, Mediterranean. *Water-Well Construction*, Manual No. 7. October 1959.

(5) Brown, R.H. *Interpretation of Pumping Test Data for Wells*, J. Am. Water Work Assoc., Vol. 45, No. 8. August 1953.

(6) Wenzel, L.K. and V.C. Fishel. *Methods for Determining Permeability of Water-Bearing Material*, U.S. Geol. Survey Water Supply Paper 887. 1942.

(7) Jacob, C.E. *Drawdown Test to Determine Effective Radius of Artesian Well*, Proceedings, Am. Soc. Civil Engineers, Vol. 72. May 1946.

(8) Ferris, J.G. *Ground-Water Hydraulics*, U.S. Geol. Survey Ground-Water Note No. 28. August 1955.

(9) Bruin, Jack and H.E. Hudson, Jr. *Selected Methods for Pumping Test Analysis*, Ill. State Water Survey, Rept. of Investigation No. 25. 1955.

(10) Bierschenk, W.H. *Hydraulic Characteristics of Hanford Aquifers*, Hanford Works Document No. HW-48916, Office of Technical Services, U.S. Dept. of Commerce. 3 March 1957.

RECONNAISSANCE METHODS OF LOCATING STOCK WELLS IN ARID REGIONS OF THE UNITED STATES (*)

H. V. PETERSON

ABSTRACT

The arid and semiarid climatic zone in the Western States contains an area of 300-400 million acres. The major part of this land supports a sparse vegetative growth, valuable only as forage for grazing. For optimum use of the forage by livestock, water should be spaced at intervals of 5 miles or less. Some water for livestock is provided by permanent streams and springs, but for most of the area surface reservoirs or wells provide the only source. Wells are preferred since they provide a permanent and reliable supply but they have the disadvantage that costly drilling may result in dry holes.

Geologists of the Geological Survey in their work of assisting the land agencies in selecting well sites, employ reconnaissance methods of examinations. In this, any possible aquifer underlying the prospective site is identified and an attempt is made to evaluate its yield potential through studies of the rock and of its outcrop area Geologic sketches and maps may be used to trace aquifers from known into unknown areas.

Because the yield of most stock wells need not exceed 5-10 gpm (gallons per minute) a variety of aquifers that would be unsatisfactory for larger wells will qualify as a source for stock wells. These include alluvium of varying texture, moderately permeable consolidated rock, and some dense rocks made sufficiently permeable by joints and fractures. In evaluating the potential of any prospective aquifer, the geologist takes advantage of any available evidence relating to the occurrence of ground water. Wells in the vicinity are studied to obtain information on the aquifer and the level of the water table. Features such as seeps, springs, streams and phraetophyte growths are investigated since they are important indicators of ground-water occurrence and movement and may show the approximate position of the water table. For these reasons, they are of value in locating possible aquifers and in selecting favorable drilling sites.

The proportion of successful wells obtained at sites selected by experienced geologists is relatively high. Reasons for the successful and unsuccessful completions based on experience gained in the past several years are studied in an effort to improve the percentage of successes.

RÉSUMÉ

Les zones climatiques arides et semi-arides des Etats de l'Ouest couvrent une superficie d'environ 300 à 400 millions d'acres. La plus grande partie de ces terres produit une végétation pauvre et clairsemée qui n'a de valeur que comme fourrage pour le pâturage. Pour employer ce fourrage au maximum des points d'eau devraient être espacés à des intervalles de 5 miles ou moin. Des sources et des ruisseaux à écoulement permanent fournissent de l'eau pour le bétail, mais la plus grande partie de la région dépend de puits et de réservoirs en surface pour son eau. On préfère les puits qui présentent plus de sûreté et de permanence, cependant ils ont le désavantage que de coûteux forages peuvent parfois avoir des résultats négatifs.

Dans leur travail d'aide aux agents agricoles pour le choix de l'emplacement d'un puits les géologues du Service Géologique emploient certaines méthodes d'examen du terrain. Suivant ces méthodes on identifie n'importe quelle formation aquifère se trouvant sous l'emplacement étudié et on essaie d'évaluer son rendement possible par l'études de roches et l'étendue de son affleurement.

Comme il n'est pas nécessaire que le rendement d'un puits pour le bétail dépasse 5 à 10 gpm (gallon par minute) quantité de formations aquifères qui ne pourraient être utilisées pour des puits plus importants peuvent être satisfaisantes pour des puits pour le bétail. Ces formations comprennent des alluvions de composition variable, des terrains mélangés et de perméabilité modérée et certaines roches denses que des fractures et des joints ont rendu perméables. Dans l'évaluation des possibilités de rendement d'une formation aquifère le géologue tire profit de toutes indications

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(*) Publication authorized by the Dir. U.S. Geol. Survey, Dept. of Interior.

disponibles ayant trait à l'existence d'eau de surface. On étudie les puits dans le voisinage afin d'obtenir des renseignements sur les formations aquifères et le niveau de la nappe phréatique. On examine soigneusement les suintements, les sources, les ruisseaux et les croissances phreatophytes car ce sont d'excellents indicateurs de l'existence d'eau dans le sol, du mouvement de cette eau et ils peuvent indiquer approximativement la position de la nappe phréatique. Quand la chose est nécessaire on se sert de croquis géologiques et de cartes géologiques pour suivre les formations aquifères d'une zone connue à une zone inconnue pour le choix d'un emplacement de forage favorable.

La proportion de puits à bon rendement obtenus aux emplacements choisis par des géologues avertis est assez importante. On étudie constamment les essais infructeux afin d'améliorer ce pourcentage.

The Western States contain an area of between 300 and 400 million acres lying within the arid and semiarid climatic zone. The area, in general, is typical of the World's arid zones described by Shantz (1955) and others, Sparse erratic precipitation, low humidity, high evaporation, and scant water supplies are characteristic. Some parts are extremely hot, others are temperate; a few areas are barren but most of the land produces some usable vegetation. The long term average annual precipitation ranges from 6 to 15 inches, depending on location, but droughts of several years'' duration, in which the annual precipitation may drop to 50 percent or less of the average annual, are of common occurrence. Infrequently the annual rainfall may soar to 2 and 3 times the normal. Excessively high temperatures, which compound the effect of aridity, are common only in the extreme southern part of the area, but lands in the northern latitudes with mild summers and cold dry winters are also strongly affected by the aridity.

A small part of the area, 3 to 4 percent, is irrigated and a somewhat smaller amount is potentially capable of being irrigated, using water supplies imported from more humid regions or obtained by pumping from ground-water reserves that have accumulated over a long period of time. Barren areas may be caused by a number of conditions, including extremely high temperatures and scant rainfall common to parts of the south, unfavorable soils due to alkali and salt accumulations or the presence of impervious clays and silts at the surface, and advanced wind and water erosion. The remainder of the land, comprising about 80 to 90 percent of the total is productive in some measure. This productivity is not large—in fact it has been so small that only an insignificant part of the land has passed into private ownership even under our very liberal aquisition laws. The great bulk of the land remains in public ownership, administered by agencies of the Federal Government or by the States.

The principal product of these lands is a heterogeneous association of plants of varying density and volume, valuable in the main only for the forage. Seldom is the plant growth plentiful or valuable enough to be harvested or processed except by direct grazing by livestock. Although on a unit area basis the productivity of the land is low, the total size of the area makes it an important unit in the Nation's economy. This dry range is the main pasture for more than 10 million cattle, sheep, and horses, and, in addition, it provides the principal support for about a million big game animals, an important item in supplying recreation to a fast-growing population.

To secure the optimum use of the forage and at the same time insure against erosion and other types of damage to these range lands, proper distribution of livestock is necessary. An essential factor in controlling this distribution is water for livestock use. For most effective harvesting of the forage, watering places must be spaced at intervals such that stock can reach the feed without expending excessive amounts of energy in moving from feed to water and return. For protection of the range, the spacing must be such that depletion of vegetation is avoided such as occurs when livestock are forced to concentrate around a few widely spaced watering places while much of the intervening area remains ungrazed.

Owing to differences in mobility, animals vary in the optimum distance they can travel in their quest for food and water. Horses will travel farther than cattle, some classes of cattle farther than others, and sheep the shortest distance of all. Also, all types of stock will travel farthest and still thrive where the grazing area is flat or gently sloping, where the ground is smooth not rocky, where the temperature is not excessively high, and where the forage is sufficient to keep the animals healthy and vigorous. Because of the several factors involved, it usually is not practicable to set a fixed optimum spacing for water, but experience on our Western range lands has demonstrated that the maximum spacing between waters under any conditions should not exceed 5 miles and, for most efficient use of the range, a spacing of 2 to 3 miles is desirable. An important element in the management of these range lands is to provide water at this spacing.

Range water can be obtained from a number of different sources, including streams, springs, reservoirs, and wells. Each has its advantages and limitations. Where the supply is adequate and other conditions are favorable, the service area of any source may be expanded by use of pipelines or by hauling, depending on economic considerations. The service area is defined as the area which stock can efficiently graze from any given source.

Of all the sources, perennial streams and springs obviously are the cheapest and most reliable. However, on the Western range these are not only scarce but most have long since been appropriated and are fully developed so there is no further opportunity for expansion. Accordingly, the choise for developing new stock-water places is limited to reservoirs or wells.

Stock reservoirs are in common use in most localities where grazing is practiced. In some localities, they are competitive with wells as a source of range water; in others they supplement wells; and in still others, where geologic conditions make it impossible to or impractical to obtain wells, reservoirs are the sole source of water except for supplies that might be imported by pipeline or by hauling. Advantages of the reservoirs are (1) ease of construction, which often can be carried out by the rancher with a small outlay of capital, and (2) low operation and maintenance costs since there are no power plants, pumps, troughs, and storage tanks to provide and keep in repair.

The great disadvantage of the reservoir is its lack of reliability. To be successful, the reservoir must have sufficient inflow to offset losses resulting from evaporation, seepage, and consumption by animals and by plants that may be present. In most localities these losses total several feet per year, which means that unless the pond is deep there must be frequent inflow throughout the season to maintain a permanent supply. Characteristically, the runoff from arid areas lacks this regularity of occurrence.

Proof of the uncertainty concerning runoff is shown by measurements at 48 small drainage basins distributed throughout the range lands in Western United States (Peterson, 1961). The mean annual run off measured at the stations during a 4 to 12 year period ranged between 3 and 40 acre-feet per square mile of drainage area, but each had periods ranging from 5 months to 3 years in which no runoff occurred. Obviously, range lands cannot be used efficiently where stock water may not be available for periods this long.

It might be argued that reliability of the supply could be improved by constructing bigger reservoirs on larger drainage areas, thus assuring greater carryover storage. However, this advantage is offset by the greatly increased cost of construction of big dams together with added waste of water through evaporation and seepage from the expanded storage. Downstream water users are exhibiting increasing concern over the wastage of water inherent in this type of operation. Legitimate needs of stockmen for range water usually are not challenged, but strong objections are developing to the practice of constructing more and larger reservoirs as a means of securing range water.

Because of these drawbacks and disadvantages, reservoirs have been relegated to second choice in many localities and stockmen are showing a preference for wells. Wells have the great advantage, where they can be developed at reasonable depth, in that they provide a reliable and permanent supply for stock use, and, the cost of drilling and equipping a well compares favorably with the cost of reservoir construction. Once completed in proper manner, the well lasts indefinitely and except for normal maintenance and repairs the operating cost is low. This is particularly true where windmills are used for pumping, which is the common practice except for very deep wells. But with these advantages there is one serious disadvantage: the risk the owner takes that drilling will fail to find water. In this case the cost of drilling is lost with no possible chance of recovery. Any approach, therefore, which tends to reduce this risk and to increase the probability of finding water, will be of direct benefit both to the stockmen and to the range.

During the past 20 years personnel of the U.S. Geological Survey have been assigned the task of assisting the administrative land agencies in developing conservation programs for the publicly owned range lands in the Western States. A major activity in this assignment has been that of selecting well sites in dry parts of the range These sites have been scattered throughout the 300 to 400 million acres of dry lands previously mentioned, and have involved many different types of terrain and physiographic and geologic features. From this experience has evolved what might be termed the reconnaissance approach to selecting well sites. This is not commonly a precise procedure, but one in which the examiner attempts to collect evidence and apply certain principles of geologic reasoning in predicting where and at what depths water might be found. Well-trained and experienced geologists, who have confidence enough in their own judgment to make definite and unqualified recommendations after analysis of the field evidence, have proven to be most successful in this type of work.

The examinations made are of two general types. One involves what are termed «spot locations». In these the examination is directed toward determining the prospects for obtaining a well at a particular location designated by the requesting agency. The desired site may be any where within a large grazing area where an additional range water facility is desired or it may be restricted to a relatively small area because of land ownership, allotment boundaries, natural physiographic or geologic features, or other causes. Consideration of single sites place a rather low limit on the amount of field work that can be justified for each one, as the expense of each investigation logically cannot exceed more than a reasonable percentage of the cost of drilling. Success in this type of examination is dependent largely on the reasoning and good judgement of the examining geologist.

The second type is broader in scope and usually is applied to large areas of range land. Its purpose is to develop a complete range-water development program for the most effective use of the selected area and may include all types of water facilities. The size of the area can have a wide range depending in some cases on the use to be made of the study by the requesting agency and in others on the geologic and physiographic conditions encountered. Administrative units, such as grazing districts, which may be as large as several million acres and include many grazing allotments, are commonly included in this type of study. In other situations, a geographic feature such as a valley or a drainage basin, or an area having the same geologic setting, may form the unit of study. These may include several grazing districts or other administrative units. The important item is that the large size of the area justifies a study in considerably greater detail than is possible with a single site.

In either type of examination, the geologist is faced with two questions at each individual site: is an aquifer present within reasonable drilling depth; and if so, is it pervious enough to supply the needed yield for a stock well? If the evidence indicates that the answer to both questions is affirmative, the geologist is in a position to recommend drilling, otherwise the will advise against it. In considering aquifers, the low yield requirements of a stock well make it possible to drill in locations and to test formations which could not possibly be considered if larger yields were essential. It is a generally accepted rule of our Western ranges that no more than 100 cattle or 500 sheep can be grazed within the service area of a single watering place for any protracted period without exceeding the carrying capacity of the range and causing damage. A continuous yield of 0.7 gpm (gallons per minute) is sufficient for this number of stock but because windmills, which ordinarily supply the energy for pumping, do not operate full time a larger yield sufficient to compensate for the non-operating time, must be obtained. Wells that yield 5-10 gpm are ordinarily considered satisfactory by stockmen and in some situations wells that yield only 2-3 gpm are acceptable.

The obvious first step in the examination will be to identify formations underlying the area that possess the storage and permeability essential in an aquifer. Because of the low yield requirements, a great variety of formations may qualify in this regard. These range from alluvial material having a wide range in composition and texture through consolidated rocks having different degrees of permeability to dense, well indurated rocks made permeable to some extent by fractures, planes of schistosity, and other types of minute openings.

In addition to permeability, the aquifer must also be favorably situated with regard to recharge and the direction of ground-water movement. Although it is unlikely that pumping from a stock well will ever seriously deplete an aquifer, recharge conditions must be favorable to insure that water enters the formation. Usually there is little question concerning recharge to alluvial aquifers. They may be recharged by percolation of precipitation on the valley floor and margins, or from ephemeral stream flow through the alluvial fans or other coarse sediments distributed around the valley margins. Where consolidated formations are recharged chiefly through the outcrop area, it is essential that surface conditions in that area be favorable for infiltration through the soil into the formation and also that there be a hydraulic gradient away from the outcrop which allows water movement in the direction of the prospective well site area.

Meinzer (1923) listed and described briefly the water-bearing characteristics of a large number of formations present in Western United States, ranging in age from Precambrian to Quaternary and in character from non-waterbearing shales to coarse alluvium that yields large quantities. The majority of the formations listed are described as having some potential for water supply although the yield can vary greatly from place to place, depending on facies changes, structural relations, and the characteristics of the intake area. The formations generally considered non-waterbearing, or very poor aquifers, include the dense shales, some limestones, many fine grained shaly sandstones, most of the thick clay and siltstone beds, and the dense igneous and metamorphic rocks that mostly make up the basement complex.

Of the unconsolidated rocks, alluvium is the most important aquifer owing to its wide distribution and to its permeability which, except for the varieties of very fine texture, usually is sufficient to assure ample yields for stock wells. Alluvial deposits are of special importance in the Basin and Range Province in the Western States where they constitute the major part of the fill in most valleys. Meinzer (1923, p 292) estimated that the deposits occupy about half of the total area within the province. The nature of the deposits is such that they from reliable aquifers in most localities although they can present complex problems in selecting well locations. The alluvium distributed along stream valleys may likewise form important and reliable aquifers provided the deposits are thick and extensive enough to provide substantial ground-water storage. However, most of these Western valleys have been developed for agricultural use and there is no demand for range water. Glacial drift and sand dunes can also be considered as aquifers in some localities but their restricted distribution makes them of limited value as a source of range water.

Among the consolidated rocks commonly found underlying the Western range lands, sandstones have proven to be the most reliable aquifers provided that the structural position of the beds and the intake-discharge conditions are favorable. Best results in drilling have been obtained in medium to coarse grained types, but studies by Harshbarger (1954) suggest that varieties of finer texture, in which the median diameter of the sand grains is 0.10 mm or greater and the sorting coefficient ranges between 0.75 and 1.35, will probably yield sufficient water for a stock well, provided cementation in the rock has not destroyed the permeability. Rocks with a median grain size of less than 0.10 mm generally are nonwaterbearing and should be avoided in drilling. Hard, well cemented sandstone and quartzites commonly yield small quantities of water from fractures and can be considered as potential stock well aquifers where the joints are well developed and interconnected and are so inclined that large numbers will be intersected in drilling (Meinzer, 1923, p 112).

Limestones, although widely distributed in mountainous areas of the West, are generally poor aquifers, chiefly because of the characteristic low permeability. Some limestones doubtless contain water in crevices and solution cavities, but drilling to intersect these openings involves such a large element of risk that few stockmen are willing to undertake it. No method has yet been developed for predicting from surface evidence the location of openings even with detailed geologic studies. As a consequence, our geologists generally advise against drilling in limestone unless there are obvious reasons for other recommendations.

A few of the dense igneous and volcanic rocks, such as granite, monzonite, rhyolite and andesite, have proven to be aquifers in a few localities where fracturing is extensively developed. However, drilling these rocks in dry areas is hazardous and not to be recommended except where there is proof or strong evidence that water will be encountered. Basalt that is fractured or that contains interconnected vesicular openings and scoracious zones is a good potential aquifer if other conditions relative to ground-water occurrence are favorable. Successful wells have been developed also in volcanic tuffs, breccias, and agglomerates.

The weathered equivalents of some of the igneous rocks are potential stock well aquifers. The occurrence of water in disintegrated granite overlying unaltered rock, even under desert conditions, is well known and is attested by several successful wells drilled at sites selected in our own explorations. Weathering under arid conditions, of andesite, rhyolite, felsite, and other fine textured rocks, usually produces a shallow less pervious mantle and, in consequence, prospects for developing wells are less favorable.

The above mentioned rock types, although incomplete, comprise the principal aquifers commonly encountered in our range lands. Not all of these rocks will yield sufficient water for a stock well in all places, and naturally some are superior to others, but experience indicates that where structural, drainage, and intake conditions are favorable they merit consideration as possible sources of ground water for stock wells.

The rocks mentioned are readily identified and the experienced geologist will soon come to recognize conditions under which they will likely act as aquifers. Where sedimentary rocks are involved, the should be familiar enough with the stratigraphic column to be able to forecast with considerable accuracy the strata that will be encountered as drilling proceeds. Recognition of the various rock units and their stratigraphic position at any particular locality is aided by the fact that in arid areas there is no dense vegetation to conceal the formations.

Having decided that a possible aquifer underlies the area in which wells are wanted, the geologist then has the problem of evaluating its yield potential and of determining the position of the water table, if one is present, or the depth necessary to find water where water table conditions are not present. For this purpose, the geologist will seek evidence from any available source. Thus, where ground-water data are available at a nearby location, such as at a well, the most logical procedure will be to work from the known area to the unknown. This transition may be a simple one, such as keeping tab on differences in ground elevation and position of the water table between locations in an alluvial filled valley, or it may be complex enough to require the preparation of a reconnaissance geologic map and a careful examination of the outcrops of the prospective aquifer to learn something of its water-bearing characteristics.

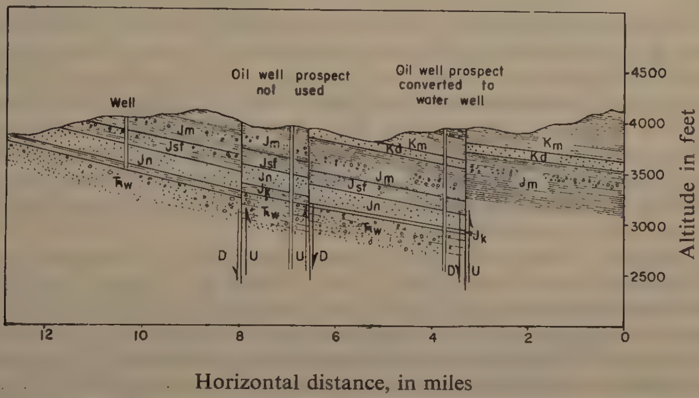
Examples of the simple transition are illustrated by the well site studies made in a number of the alluvial filled valleys in the Basin and Range Province. Existing wells, although usually few and widely scattered, show that most of the valleys have a water table that slopes toward the center of the valley, where the valley has no outlet, or in the direction of surface drainage if there is an outlet. Where enough well measurements are available, water-table contours can be drawn and the water-table gradient can be established. There is thus developed a basis for predicting the depth to water at any particular location where the ground elevation is known. Where no maps of the valleys are available, simple sketches or profiles depicting the relation between the ground surface and water-table elevations can be prepared quite readily. Altitudes can be determined by using an aneroid barometer, with corrections for barometric changes; distances can be measured by pacing or by using an automobile; and a position can be plotted by use of a compass.

A more complex problem requiring the examination of outcrops and the preparation of reconnaissance geologic maps occurs when it is necessary to trace the continuation of possible consolidated aquifers, such as sandstones, for considerable distances and to determine their position at a prospective well site. This can be greatly complicated by intervening faulting or folding, but with reasonable care in preparation the geologic sketch can be made to depict the position of the possible aquifer with the accuracy desired. For this type of work the geologist must be experienced enough to recognize the structures and to evaluate their effect on the movement of ground water. Again the aneroid, the compass, and the automobile are the essential articles of equipment needed in preparing the sketch, but naturally considerably more time and care will be required to observe, locate, measure, and appraise features of the formation that will give some clue regarding its water-bearing characteristics.

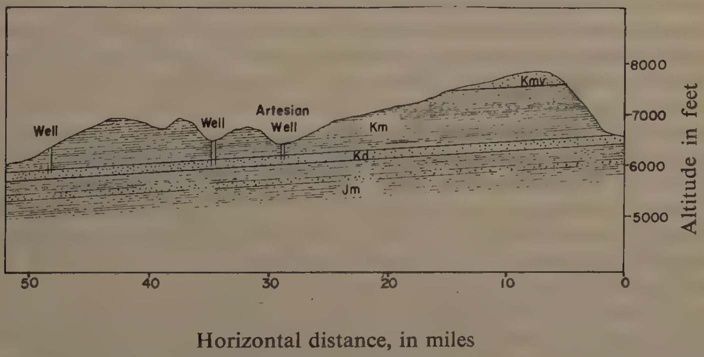
Figures 1-A and 1-B are sketches developed in the manner suggested above As indicated, two of the wells shown on figure 1-A were drilled as unsuccessful oil prospects and abandoned, but both had found water in the sandstones. The well on the right was later plugged and developed as a stock water well. The new well at the extreme left was drilled for stock water knowing that the underlying sandstones had proven to be aquifers in the oil well tests. The faulting here did not greatly influence the drilling since either of the underlying sandstones could be considered as a potential aquifer. The area, located in east-central Utah, has an average annual rainfall of less than 8 inches but because of the sandy soil the infiltration is high and the forage production is good. Prior to drilling the wells the area was unused for grazing. Although in this case the oil prospects had proven the sandstones as aquifers, the geologist would have recommended drilling without such proof because of the favorable character of the sandstone, the large recharge area, and the excellent structural position.

Figure 1-B is a sketch of a simple monoclinal structure in northwest Arizona in which the position of the aquifer, the Dakota sandstone, is depicted. Using similar sketches it has been possible to predict with fair accuracy the depth of drilling at several well sites in this general area. Flowing wells were obtained at some sites and at most of the other sites there was a strong artesian rise. Sketches of this type can be completed in a few hours where there are roads with only a car, a barometer, and compass for instrumentation.

Fig. 1


Well
Oil well prospect not used
Oil well prospect converted to water well
Jm
Jsf
Jn
Jk
Ѫw
Km
Kd
D
U
4500
4000
3500
3000
2500
Altitude in feet
12
10
8
6
4
2
0
Horizontal distance, in miles

A. Colorado Plateau, Utah. Section showing position of 3 wells which obtain water from 3 separate sandstone formations.



B. Colorado Plateau, Arizona. Wells obtaining water from Dakota sandstone. Knowing position of formation, depth of drilling needed to obtain water can be closely estimated.

EXPLANATION

Km — Mancos shale
Kd — Dakota sandstone
Jm — Morrison formation
Jsf — San Rafael group, undifferentiated
Jn — Navajo sandstone
Jk — Kayenta formation

In areas where wells or other direct information on the occurrence of ground water is lacking, the geologist must seek evidence from other sources that might give some clue as to the prospects for successful drilling. One type of evidence is the presence of water loving plants called phreatophytes (Meinzer 1927), which habitually grow in localities where they can send their roots to the water table. The plants are evidence of a moderately shallow water table, as it has been shown by experience that 50 to 70 feet is the maximum depth from which they can extract water. Within this depth they are usually reliable indicators of ground water although it should not be concluded that absence of the plants is an indication that there is no ground water within the 50-70 foot depth. A description of the more common phreatophytes and their growth characteristics is given by Meinzer, 1923 and by Robinson, 1960.

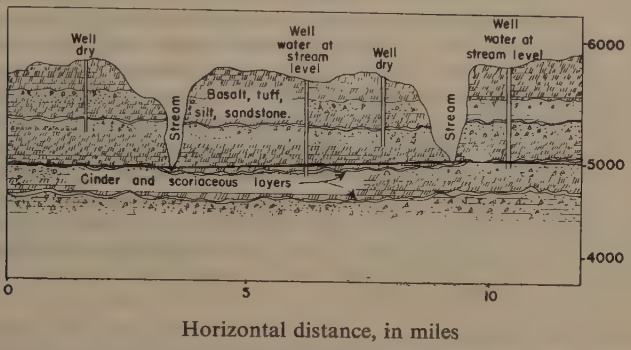
Phreatophytes occasionally represent important evidence of ground-water conditions in other ways than by showing the presence of a water table. Assemblages of the plants found growing in locations isolated from a regional water table obviously are subsisting on ground water issuing from a rock formation and the plants thus furnish evidence of permeability and water movement within the formation. Wells that tap the formation at the horizon from which the water is issuing have a good chance of being successful. Willows and other familiar phreatophytes growing along a seepline at the contact between shale and an overlying sandstone represent a familiar example of this type of evidence.

Springs and seeps found in any location are evidence of groundwater movement and thus merit special consideration by the investigating geologist. As pointed out by Tolman (1937) most springs issue at the outcrop of an aquifer or in pervious material overlying an aquiclude. It follows therefore that the formation from which the spring issues represents a potential source area for developing successful wells. One particular variety of seep, that found issuing from fractured rock, has proven to be of special value in assessing the prospects of developing wells in certain formations. On the basis of such seeps, successful wells have been drilled in bodies of schist located in some of the driest parts of Arizona and Nevada. The yields are low, 2-5 gpm, but sufficient for the needs of the surrounding area. Except for presence of the seeps it is unlikely that the formations would have been considered favorable for well development. Other types of springs may be equally valuable in judging the prospects for obtaining wells and each should therefore be thoroughly investigated by the examining geologist.

Other evidence indicative of the position of a zone of saturation may be found by observing the behavior of streams. Although perennial streams are scare in desert areas, the few that are found often furnish information on ground-water conditions. An influent or increasing stream, for example, is evidence that the stream is being fed from a pervious formation which logically can be considered as a possible aquifer at locations remote from the stream. An effluent or loosing stream on the other hand indicates that the stream is in contact with a permeable but unsaturated formation, and suggests that drilling to a horizon considerably deeper than the stream level will be necessary for development of a successful well.

An example of the value of this type of evidence is sketched in figure 2 which shows a section through one part of the Columbia Plateau in northern Nevada. The two canyons are occupied by forks of the Owyhee River, a permanent stream. Examination showed no evidence of seepage along the canyon walls, although the rock was pervious. However, there were indications of small influent flow at stream level. Several dry holes located on the plateau between the streams had been drilled to depths of 300 to 500 feet, which was about 200 feet above stream level. Concluding that the influent flow at stream level was a favorable indication of ground water, it was recommended that the wells be drilled to this depth. To date, all wells drilled to this level have been successful and even though drilling depths of 1,000 feet have been required in some cases, the value of the additional forage made available because of the wells has justified the expense.

Fig. 2



Columbia Plateau, northern Nevada. Weak pervious rocks consisting of basalt, tuff, siltstone, and sandstone cut by deep canyons. Water table is controlled by level of streams.

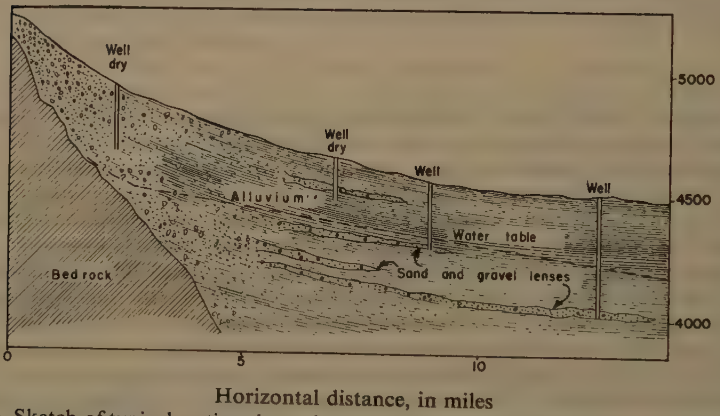
Although it might appear that locating wells in alluvium should be less complicated and involve less risk than with consolidated rock aquifers, experience has demonstrated that alluvial areas may also present many problems due in the main to the unpredictable nature of the deposits. Alluvial filled valleys comprise a large part of the range lands in Western America and in fact alluvium is probably the commonest of all aquifers. Geologically, most of the valleys appear to have the form of a depressed block partly filled with debris washed in from the surrounding mountains. The fill may range in thickness from a few hundred to more than a thousand feet. Where deposition is from the surrounding mountains, coarse debris is deposited around the valley margins and fine often impermeable sediments toward the center. Usually wells located near the margins are successful but in the central parts of the valley the wells are likely to be dry unless they penetrate lenses or stringers of pervious material that extend in from the valley sides. Quality changes are noticeable too. At the margins of the valley the quality is generally good but in the center, where playas occur, the water may be highly saline.

The depth of drilling required to find water in the valley may by uniform throughout or it may vary greatly because of local conditions of sedimentation. The point is illustrated in figure 3-A which is a cross-sectional sketch of a southern Arizona valley. In the successful well on the left reached water was found at about 300 feet, but in the one on the right it was necessary to drill to 500 feet. Had it not been that this well was fortuitously drilled into a lens of permeable sand it would have been dry, because the surrounding very fine textured fill would not yield even the small amount needed for a stock well. Water in this well rose to the projected level of the water table, but as can be seen, this level is not always a reliable indication of the depth of drilling needed to obtain a well in other parts of the valley.

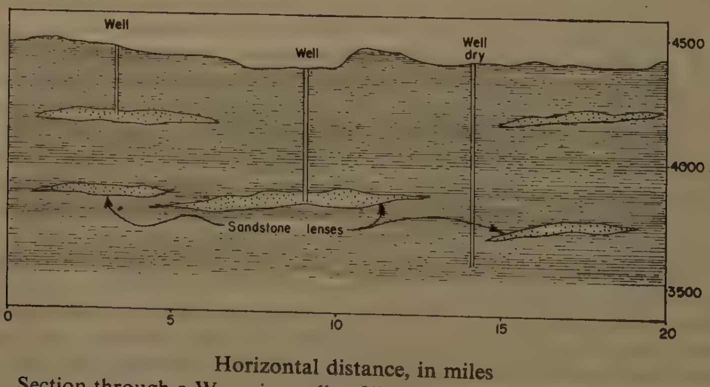
Attempting to locate pervious stringers and lenses of gravel and sand, such as those depicted in the sketch, is one of the most difficult tasks faced by the geologist in selecting sites in alluvial valleys. There is seldom any surface reflection of the features, yet it is known that they are of rather common occurrence. Geophysical methods using electrical resistivity have been tried in a number of localities, with indifferent or negative results. Seismic methods should prove more reliable but the high cost of such surveys in the past has prohibited their use. However, there are prospects that recently developed equipment will materially reduce the cost.

Although similar in appearance, many of the alluvial valleys contain deposits quite different from those described above. Some are filled with impermeable lake beds of fine texture that extend to the very margin of the valleys. In others, the deposits appear to have been laid down by through-flowing streams resulting in a sediment pattern that differs considerably from the pattern established by streams draining from the valley sides. The development of wells in either type of valley involves an added risk, and it is important therefore that such valleys be recognized and thoroughly explored by the examining geologist. Lake beds are seldom pervious enough to yield sufficient water for a stock well and should be avoided in drilling. Occasionally water can be obtained in recent alluvium overlying the lake beds and in rare cases good wells have been obtained by drilling through the lake beds into the basal conglomerate of coarse texture. The latter will generally mean deep drilling and should be undertaken only where there is strong evidence that the conglomerate contains recoverable water of satisfactory quality.

Fig. 3



A. Sketch of typical section through valley in Basin and Range Province. Relatively pervious alluvium near valley sides; interior relatively impervious except for sandy lenses.



B. Section through a Wyoming valley filled with consolidated shale and siltstone containing sandstone lenses. Well will be successful only if a sandstone lense is encountered.

Figure 3-B illustrates one case of a valley fill that appears to have been laid down by a through-flowing stream. The fill consists of shale and siltstone containing interbedded lenses of sandstone occuring at several different horizons. The shale and siltstone are relatively impervious but wells that penetrate the sandstone lenses are productive. As the position of the sandstone lenses cannot be predicted from surface indications, success in drilling in the area involves an increased risk which the stockman may or may not wish to assume, depending on the value of his unused range.

The examples above illustrate a few of the problems encountered in selecting well sites in alluvium filled valleys and they emphasize the need for careful study and the exercise of good judgment on the part of the geologist. One of the drawbacks connected with these studies is the difficulty of obtaining good logs of the wells. Logs of the old wells seldom are available, and even in present-day drilling most drillers either do not have the facilities or do not take the time to obtain an accurate log. Thus the geologist is severely handicapped in his effort to interpret subsurface conditions. We are hopefully carrying on a campaign to educate well drillers on the importance of logs in their current and future drilling as an aid to securing better information of ground-water conditions in these valleys.

Following the procedures developed in the reconnaissances described above, personnel of the U.S. Geological Survey during the past 20 years have examined and reported on more than 1,000 well sites scattered through the Western States. Of these, less than one-quarter have been drilled, but there are valid reasons for this low percentage. Recommendations against drilling were made at a number of sites which had been suggested by stockmen or others, because of unfavorable geologic conditions. In a number of areas, several sites were considered as a group with the recommendation that drilling proceed in a given sequence. Thus, one failure could eliminate a number of sites. At several sites the estimated depth to water was considered by the stockman to be excessive for the amount of forage available. These sites could conceivably be drilled in the future should the forage improve or the range becomes more valuable. Finally many of the sites are considered as part of a long term program of range improvement with the expectation that they will be drilled in the future as the program advances.

The proportion of successful wells obtained at recommended sites where drilling has been completed is believed to be between 85 and 90 percent. Reasons for the failures have been closely scrutinized in an effort to improve this percentage. It it known that in several failures the geologist had recognized that conditions were nos altogether favorable for obtaining water and had so advised the stockman but a greater risk was taken, with the stockman's concurrence, because of the urgent need for water at the location. Most failures can be attributed to the condition that permeability of the prospective aquifer was less than the geologist had anticipated and was not sufficient to furnisch the needed yield. In some instances subsurface conditions had been misinterpreted, due mainly to features not in evidence at the surface. In a few cases reasons for the failure were not clear.

In view of the fact that all the well locations were made in dry areas where water in any form is in short supply, the success achieved to date is considered noteworthy. Despite the infrequent failure, the work of the examining geologists has come to be held in such high regard that most of the land agencies now insist on an examination and favorable report by a Survey geologist before drilling of any proposed well site on public lands is approved.

REFERENCES

Harshbarger, J. W. and Repenning, C. A., 1954, Water Resources of the Chuska Mountain Area, Navajo Indian Reservation, Arizona and New Mexico: *U.S. Geol. Survey Cir.* 308, pp 3-6.

Meinzer, O. E., 1923, The Occurrence of Ground Water in the United States with a Discussion of Principles: *U.S. Geol. Survey Water-Supply Paper* 489, pp 258-263.

— 1927, Plants as Indicators of Ground Water: *U.S. Geol. Survey Water-Supply Paper* 577.

Peterson, H. V. and others, 1961, Hydrology of Small Watersheds in the Western States: *U.S. Geol. Survey Water-Supply Paper* 1475-E, in publication.

Robinson, T. W., 1958, Phreatophytes: *U.S. Geol. Survey Water-Supply Paper* 1423, pp 33-78.

Shantz, H. L., 1956, History and Problems of Arid Lands Development. The Future of Arid Lands: Pub. No. 43, American Association for the Advancement of Science, pp 3-24.

Tolman, C. F., 1937, Ground Water: McGraw-Hill Book Co., New York, pp 435-464.

ACTION OESTROGENE DES SUBSTANCES ORGANIQUES DE LA BOUE DE QUELQUES SOURCES THERMALES DE LA GRECE

N. LOUROS, B. TERZIS, M. PAVLATOU et A. EVANGELOPOULOS

RÉSUMÉ

On a cherché à mettre en évidence l'existence probable d'oestrogènes dans la boue de quelques sources thermales grecques.

La méthode chimique et biologique nous a permis à deceler dans la boue de quelques sources des substances ayant une action oestrogène.

L'action thérapeutique des sources thermales, bien que connue depuis la plus haute antiquité, demeure encore en majeure partie mystérieuse. Les nombreuses recherches qui lui ont été consacrées n'ont réussi à jeter quelque lumière que sur des côtés partiels de la question. On en est encore sur le terrain des hypothèses et l'on doit avouer qu'aucune de celles-ci ne parvenant pas à serrer entièrement les faits, ne satisfait l'esprit.

Les propriétés physiques des sources, et surtout la chaleur à laquelle l'homme a eu de tout temps recours pour être soulagé de la douleur, le pouvoir d'absorption par la peau des substances organiques et anorganiques ne doivent être en fin de compte que partiellement prises en considération. Toute étude à ce sujet doit donc fatalement être empreinte d'un esprit de résignation.

La difficulté reste entière d'autant plus que l'analyse chimique d'un agglomérat de substances organiques n'est pas chose facile. D'ailleurs très peu d'eaux minérales contiennent des substances organiques en quantité suffisante pour en permettre une bonne étude. D'autre part la notion de la chaleur est en partie contredite par le fait que l'on rapporte de très bons résultats par l'emploi de boues froides.

La radioactivité enfin constitue encore un domaine presque inabordable.

Les impuretés, qui jadis étaient considérées comme des substances nuisibles, contiennent des substances organiques, qui expliquent en grande partie l'action chimique, biochimique et thérapeutique des boues des eaux des sources thermales et qui ont une action comparable à celles des sels minéraux, des gaz solubles, des substances colloïdes, etc. (1). L'action thérapeutique de ces substances organiques peut être interprêtée, ainsi que certaines expériences semblent l'avoir prouvé, d'une part par l'absorption de substances actives par la peau, d'autre part par l'irritation locale de celle-ci et par l'action réflexe sur les systèmes organiques à cause de leur interdépendance indiscutable. En ce qui concerne cette interdépendance fonctionnelle entre la peau et les organes génitaux internes on peut consulter avec profit les travaux de FISCHER, KROHN et ZUCKERMAN (1936) (2).

Depuis 1933, S. ASCHEIM et W. HOLWEG (3) et ensuite A. BUTENANDT et H. JACOBI (4) EULER et HELLSTONE (5) ont trouvé des substances présentant une action oestrogénique dans la nature morte (substances bitumineuses, pétrole, naphte, tourbe, etc.) PANGALOS (6) en Grèce a trouvé des oestrogènes dans les fleurs de sauge (Salvia officinalis). MOMIGLIANO (7) a pu provoquer l'apparition de l'oestrus chez la rate impubère après injection d'extraits végétaux. D'autres chercheurs dans divers pays, ont trouvé des substances ayant une action oestrogénique dans les limons et les marais. (8-15)

Certaines eaux thermales de Grèce jouissent depuis très longtemps de la réputation, parfois justifiée d'alleurs, d'exercer une action favorable sur quelques anomalies d'ordre gynécologique, comme par exemple la stérilité.

Les travaux faits en Grèce en ce qui concerne les sources thermales ont été jusqu'à présent limités à l'analyse des eaux du point de vue de substances anorganiques et de leur radioactivité (^{16}). Ainsi avons-nous cru intéressant de chercher l'existence de substances à action oestrogénique dans les boues et les eaux des sources thermales de notre pays. Nous citons plus bas les résultats que nous avons obtenus après l'analyse des limons des sources thermales ci-dessous.

1. Source Vouliagmeni;
2. Source Methanon;
3. Source Aidypsos A (source trouvée sur les hauteurs entre les sources des Saint-Anargyri et la source Papaioannou);
4. Source Aidypsos B;
5. Source Aidypsos C (source Papaioannou);
6. Source Aidypsos D (source Liatsika);
7. Source Ikaria (source Moustafa);
8. Source Ikaria (source Spilia);
9. Source Thermopyles.

La recherche des substances en question a été tant faite par la méthode biochimique que biologique.

1. METHODE BIOCHIMIQUE :

Nous avons utilisé la méthode préconisée par le Professeur JAYLE et O. CREPY (^{17}). Après l'hydrolyse et l'extraction on fait la mesure colorimétrique, par cette méthode on détecte d'une part les phénolstéroides et d'autre part la folliculine (oestrone, oestriol et oestradiol). Les phénolstéroides qui sont composés de la folliculine proprement dite et de chromogènes apparentés donnent une réaction de KOBER atypique, mais sont détectés par mesure photométrique de la décoloration de la réaction de KOBER. On réalise la mesure spécifique de la folliculine en appliquant à la réaction de KOBER la formule de correction d'ALLEN (^{18}). Cette formule permet d'éliminer les chromogènes qui n'ont pas leur maximum d'absorption à 510 m μ. Il est nécessaire pour cela de prendre la mesure à trois longueurs d'onde différentes à 510 m μ (maximum d'absorption de la réaction de KOBER), d'autre part à 470 et 550 mμ longueurs d'onde équidistantes de la première. Les résultats sont exprimés en γ d'oestrone par kg de boue humide desséchée.

Il faut souligner que les résultats obtenus par la méthode biochimique mentionnée plus haut (voir tableau ci-dessous) sont exprimés en oestrone parce que nous avons utilisé l'oestrone pour l'étalonnage du photomètre. Il s'agit de substances de constitution chimique inconnue, extraites des boues suivant un procédé comparable à celui indiqué par M.F. JAYLE pour le dosage des phénolstéroides et de la folliculine dans les urines, qui donnent une réaction de KOBER positive comme des substances de constitution chimique définie.

On est parvenu au cours de ces dernières années à mettre au point une méthode qui permet de déterminer spécifiquement l'oestriol, l'oestrone et l'oestradiol, englobés sous la dénomination de folliculine, d'oestrogènes où de phénolstéroïdes.

Nous nous proposons dans un proche avenir de reprendre nos expériences, en utilisant la méthode de BROWN pour identifier ces substances inconnues à fonction oestrogène.

2. DOSAGE BIOLOGIQUE :

Le dosage biologique des oestrogènes est basé comme on le sait sur l'apparition de réactions spécifiques au niveau de récepteurs sensibles et plus spécialement l'appari-

Source	Couleur de la boue	Quantité d'eau p. 100 gm des échantillons examinés	Phénol-stéroïdes en γ d'oestrone	Folliculine p. 1000 gm de boue en γ d'oestrone	Dosage biologique des oestrogènes p. 1000 mg de boue en unites-rat
Vouliagmeni	Gris	51	79	+++ (= 30 γ)	120
Methanon	Brun-noir	40	75	++ (= 20 γ)	—
Aidypsos A	Gris	66	93	++ (= 20 γ)	105
Aidypsos B	Gris	57	33	+ (= 10 γ)	70
Aidypsos C	Gris	42,5	63	++ (= 20 γ)	40
Aidypsos D	Rouge	—	5	—	Négatif
Ikaria (Moustafa)	Gris-noir	66	270	++++ (= 80 γ)	233
Ikaria (Spilia)	Gris	23,25	147	+ (= 10 γ)	120
Thermopyles	Gris-noir	—	5	—	—

tion de l'oestrus chez la rate castrée ou l'augmentation du volume de l'uterus chez la rate impubère. Il nous faut souligner que les tests biologiques dont nous disposons ne donnent pas de résultats identiques, parce que ces résultats sont influencés par plusieurs facteurs, comme par exemple la sensibilité des animaux utilisés, la voie d'administration de la substance à étudier et suivant aussi le récepteur choisi.

Rappelons que l'unité internationale d'un extrait correspond à la quantité de cet extrait qui produit chez la rate castrée un effet analogue à celui réalisé par 0,1 γ d'oestrone. Allen et Doisy (^{19}) ont défini comme unité rat la plus petite quantité d'oestrogène qui provoque l'apparition de cellules kératinisées au frottis vaginal d'une rate castrée de 140 g.

Comme un grand nombre de facteurs influent sur la réponse des récepteurs la plupart des auteurs admettent la nécessité d'utiliser au moins vingt animaux pour un seul essai après avoir au préalable apprecié la sensibilité à l'oestradiol des rats castrés, afin de n'utiliser que ceux qui réagissent a 0,1 γ d'oestradiol. Si les rats sont castrées depuis longtemps, il faut les sensibiliser à nouveau à l'oestradiol en leur injectant 2,5 γ d'oestradiol deux jours de suite et en les laissant ensuite au repos pendant dix jours avant l'essai préalable effectué avec 0,1 γ d'oestradiol.

En ce qui concerne l'interprétation des frottis vaginaux, la plupart des auteurs admettent qu'il faut 50% de celulles kératinisées au minimum pour démontrer l'existence de l'oestrus. La coloration des frottis a été faite selon la méthode préconisée par PAPANICOLAOU. Le résidu sec de l'extrait éthéré d'une quantité donnée de boue était repris dans une certaine quantité d'huile d'olive et injecté ainsi sous la peau du dos de rates castrées. Le calcul en unités-rat de la quantité des substances oestrogènes contenues dans l'extrait injecté a été fait par comparaison des résultats obtenus après injection de quantité minimum d'oestradiol suffisante pour provoquer l'oestrus.

3. CONCLUSIONS ET RESUME

1. — On a cherché à mettre en évidence l'existence probable d'oestrogènes dans la boue de neuf sources thermales grecques.

2. — Cette recherche s'est avérée positive dans sept sources sur les neuf examinées, et l'examen chimique a permis de déceler des taux de phénolstéroïdes et de folliculine oscillant respectivement entre 75-250 γ et 10-80 γ par 1.000 g de boue.

3. — Ces résultats ont été confirmés par l'expérience biologique.

BIBLIOGRAPHIE

(1) S. Dontas : *Pharmacologie,* Vol. 2, 1926, 164, 264.
(2) Fischer, Krown, Zuckerman : *Berl. Physiol.* 100 1936, H.3/4.
(3) S. Ascheim, W. Holweg : *Deuts. Med. Woch. 59*, 1933, 12.
(4) A. Butenandt, H. Jacobi : *Zeits. Physiol. Ch.* 218, 1933, 104, BSC.
(5) Euler, Hellstone : *Archiv. Kemi, Mineralogi. ach. Geologi, 9,* 1932, 11, *Bull. Biol. Pharm,* N. 21 1933, 198.
(6) G. Pangalos, cité dans Gynécologie : N. Louros, 1952, 50
(7) Momiglanio : *Atti Soc. Ital. Ostetr.* N. 2, 1937
(8) Gierhake et Wehefritz : *Deutsc. Med. Woch.*, 1936.
(9) Jegorow : *Akùs. i Ginekol. 11*, 1936
(10) G. Schikatauv, A. Derchawine : *Akùs. i. Ginekol. 54*, 1937, 9
(11) Munteanu : *Deuts. Med. Woch. 1*, 1937.
(12) V. Kilian : *Klin Woch. 16*, 1937, 1316.
(13) B. Weis : *Internat. Kongr. Geburtsh. 2*, 1938, 503.
(14) A. Crastins : *Arch. Gyn.* 169, 1938, 184.
(15) G. Babagagnolo : *Bull. Sté Chim Biol. 2*, 31.
(16) M. Pertessis : Recherches géochimiques en hydrologie 1955, Athènes.
(17) M.F. Jayle et O. Crepy : *Bull. Soc. Chim. Biol. 32*, 1950, 11, 1067.
(18) W. M. Allen : *Clin. Endocr. 10*, 1950, 7.
(19) W. M. Allen : et Doisy, cités dans Guy-Poumeau-Debille, Techniques biologiques en endocrinologie expérimentale chez le rat. Masson et Cie 19, 107.

PLANNED EXPLOITATION OF THE AQUIFER FEEDING THE NA'AMAN SPRING

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SYNOPSIS

The average yield of the Na'aman spring in the Northern Israel, near Haifa, was 43 MCM/year of water with a salinity of 650–700 p.p.m. Cl ion. The aquifer feeding the spring consists of limestone and dolomite of Turonian-Cenomanian age and is exploited by wells which now yield an average annual supply of 25 MCM/year of fresh water. As a consequence yield of the spring has been sharply reduced.

Salinity is kept under observation by frequent analyses and with the aid of an observation well specially constructed for this purpose. Yearly water balances of the aquifer are calculated from the decay characteristics of spring discharge and water levels, correct ed for the dynamic influence of pumpage. Forecasts of the spring yield can be worked out on a yearly and monthly basis.

It is intended to divert the maximum safe yield of fresh water from the aquifer by pumping in wells and use the residual saline flow of the spring for industrial purposes and fish ponds. Hydrological directives were formulated towards this end but their implementation was delayed by technical limitations and a succession of extremely dry years.

1. DESCRIPTION OF THE AQUIFER (Conf. Fig. 1)

The Na'aman spring issues in Northern Israel at a distance of 12 km to the N-E of Haifa. During the period 1950/1951 to 1953/1954 the spring yielded an average of 43 MCM/year (million cu.m./year) with a salinity of 700 p.p.m. Cl-ion (1600 p.p.m. total dissolved solids). Average seasonal variations of springyield were during this same period, 2.3 cu.m./sec. in spring and 1.5 cu. m./sec. in autumn.

Because of its high salinity use of the water was limited to fish ponds and industrial uses.

The catchment area which feeds the spring extends over about 220 km^2 of hilly country, composed mainly of limestone and dolomite of Turonian-Cenomanian age (Ref. 1). Average rainfall on the catchment area amounted to 650 mm/year during the period 1921-1950, indicating semi-arid conditions.

Many wells were drilled into the aquifer which feeds the spring (limestone and dolomite) and are currently exploited ar a rate of 25 MCM/year of water with an average salinity of 150 p.p.m. Cl-ion. As a consequence yield of the saline spring was sharply reduced and it completely dried up during the summer months 1959 and 1960, after a period of extremely low rainfall and full exploitation of wells.

2. PROBLEMS OF EXPLOITATION

2.1. *The problem of the safe yield* (Conf. Figs 2, 3)

It is intended to permanently exploit the aquifer by pumping the maximum permissible yield of fresh water from the wells and using the residual amount of saline water from the spring for industrial purposes and fish ponds. The safe yield thus defined cannot be expected to be a constant annual volume but it will depend in a complicated way on yearly rainfall, location of wells, the fresh water demand curve, etc. The causes of salinity in the aquifer and the mechanism of salinization of the spring are not completely understood and this makes the problem still more difficult.

Under these circumstances, the only practical way of eventually determing the safe yield is to formulate a few basic rules for the operation of the well field and to carry out continuous observations, if necessary with the aid of special bore holes.

The chemical composition of the spring-water can be accounted for, very closely, by assuming admixture of a small percentage of water originating from the Med. Sea to the fresh water in the aquifer (Conf. Table N° 2 and Ref.2).

The wells Kefar Masaryk and Afek N° 3 (Conf. Figs. 2 annd 3) show that there exists a thick layer of brackish water, salinity of which increases with depth, at least in the western part of the aquifer.

Observations made on the pumping well Afek N° 2 show that the boundary between the two kinds of water is sharply defined. The well was drilled to a depth of 87m and encountered water of a salinity of 240 p.p.m. Cl-ion. During pumping salinity increased to 570 p.p.m. Cl-ion within a few days and remained stable at this value. A few days of rest restored the original salinity but the balance was immediately upset again by pumping. Exploitation of the well was finally discontinued in order to avoid eventual spread of salinity to the eastern part of the aquifer.

The occurrence of sea-water in the aquifer has not been proven, in any case brackish water occurs far below the theoretical position of the interface between sea-water and fresh-water. The mechanism which causes brackish water to ascend and issue through the spring at elevations of 3-5 metres above Mediterranean sea level is not known. Salinity of the spring remained remarkably constant during extreme variations of yield, even immediately before and after its complete cessation in summer 1959 and 1960.

The basic safety rule for operation of the well field is, obviously, to avoid lowering of the groundwater potential below elevation of the spring and to maintain a certain gradient towards the spring. Spring flow should never cease completely. (Water supply is now being reorganized in a way which will make it possible to avoid recurrence of the situation in 1959 and 1960).

Salinity in the aquifer is now kept under observation in the Well Afek N° 3 which was specially re-built for this purpose in summer 1960. Salinity of the spring and of the pumping wells is being checked at bi-monthly intervals. No significant changes of salinity were observed during the last three years.

The programme of observations also includes simultaneous measurements of the rest-levels in all wells twice yearly, shortly before and at the end of the pumping season. Three wells which are not currently exploited were equipped with automatic waterlevel recorders, yield of the spring and of the wells is precisely gauged. These observations make it possible to determine the hydrological regime of the aquifer rather accurately and thus aid in the planning and supervision of its exploitation.

3. DETERMINATION OF THE WATER BALANCE AND FORECAST OF SPRING FLOW

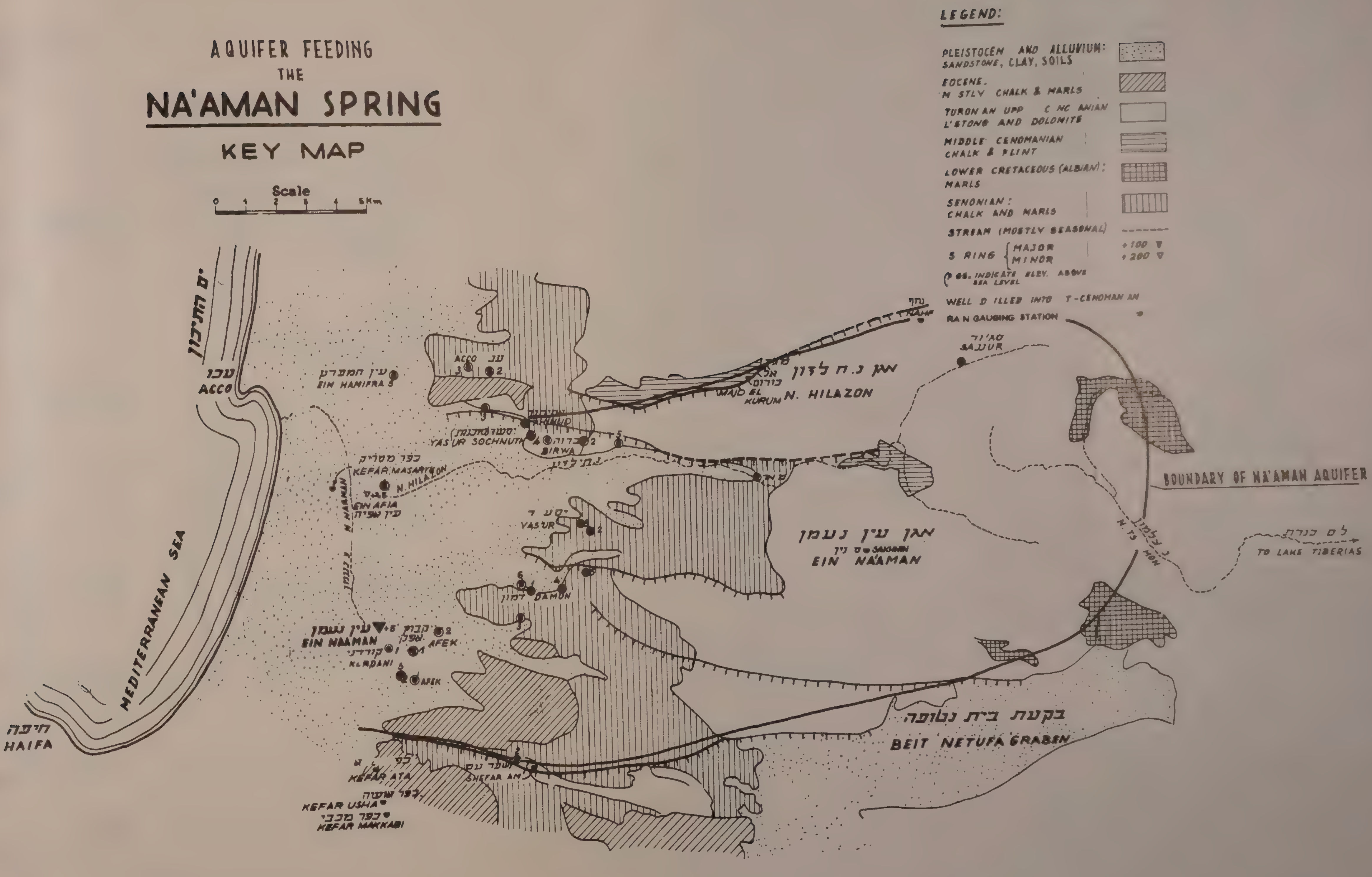
The reservoir capacity of the aquifer was calculated by F. Mero from the decay characteristics of the spring discharge, and of the water levels (Ref. 3). In the natural system discharge is a function of the reservoir of water in the aquifer so that it is possible, in principle, to deduce the water balance from the hydrograph of the spring. It is also possible to forecast the hydrograph of the dry season from gaugings carried out immediately after the rains.

However for the highly disturbed aquifer of the Na'aman forecasts can no longer be made in this simple way. Pumpage in the many wells not only accelerates depletion of the reservoir but also causes cones of depression which gradually spread towards the spring and bring about an additional reduction of its discharge.

AQUIFER FEEDING
THE

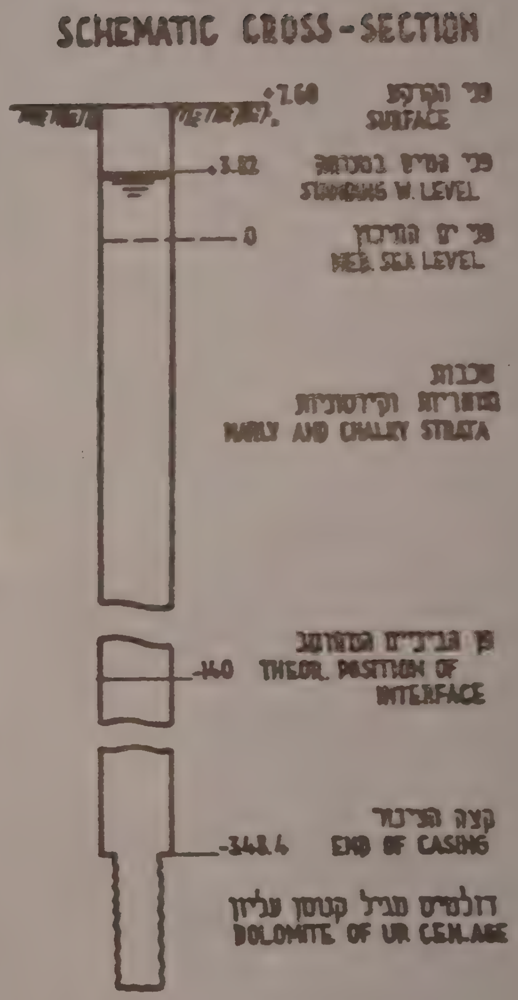
NA'AMAN SPRING

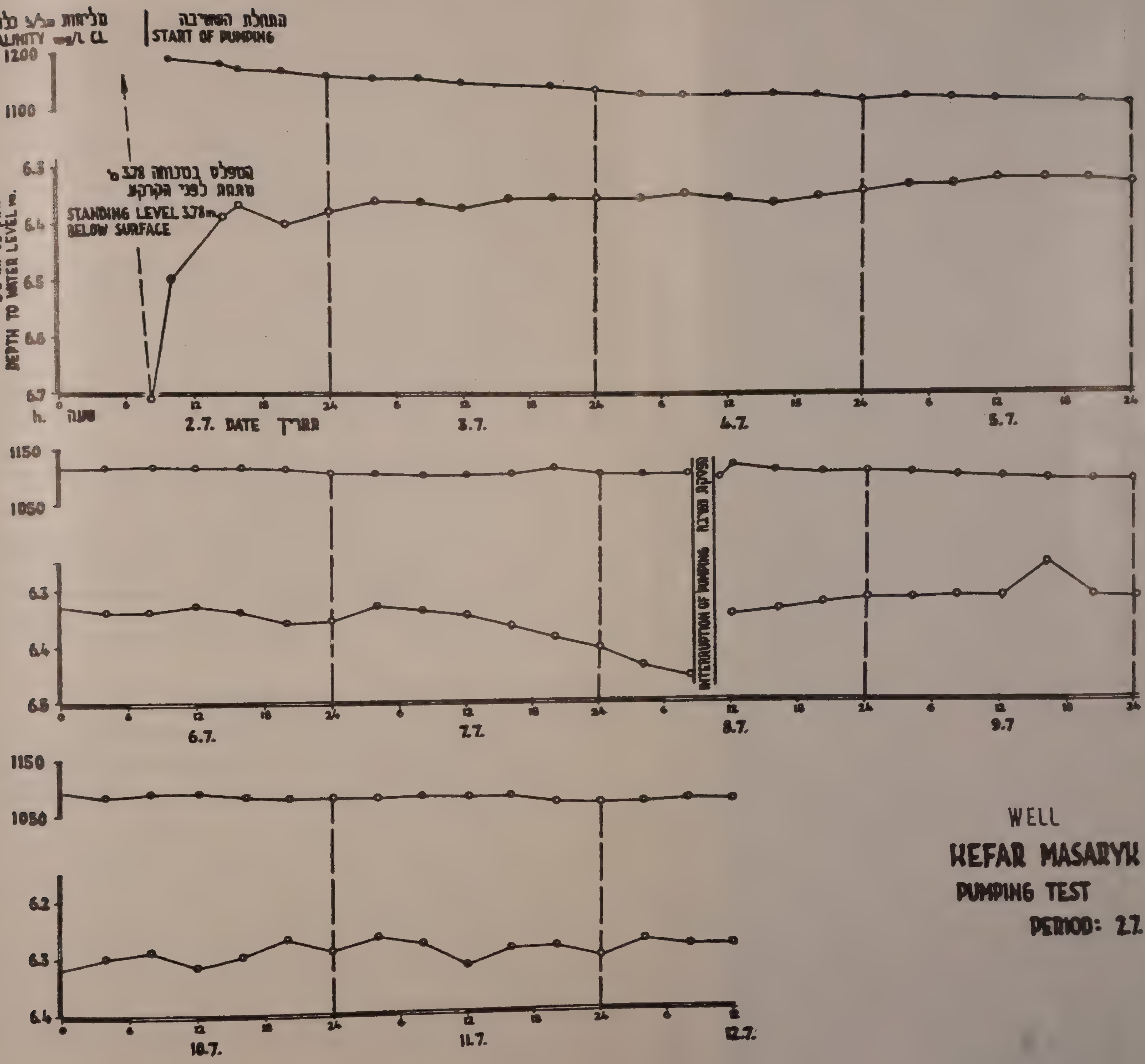
KEY MAP



GEOLOGY (SIMPLIFIED) ACC. TO MAP BY L. PICARD גיאולוגיה לפי ל. פיקרד

FIG.—1





WELL

KEFAR MASARYK

PUMPING TEST

PERIOD: 2.7.–12.7.57

FIG. — 2

This „dynamic" influence of pumpage was determined empirically from observations. (Complicated and partly unknown boundary conditions preclude theoretical calculation).

The wells could be classed in three groups : The wells of Afek-Kurdany which are nearest to the spring almost immediately reduce its flow by about 90% of the pumped yield. The centre of gravity of the Damun wells is about 6 km distant from the spring and these wells reduce spring flow by about 60% of the pumped yield within a month after start of pumping. The dynamic influence of the Birwah-Yassur wells does not exceed 15% of the pumped yield within a month after start of pumping.

The most efficient scheme for exploiting the aquifer would be to operate the Afek-Kurdani and Damun Wells in winter, spring and early summer only, in late summer and autumn pumpage should be shifted to the Birwah-Yassur wells. With this way of operation spring discharge could be kept at a certain minimum throughout the year, thus fulfilling the basic safety rule and also making easier the exploitation of saline water.

The precise plan of operation should be worked out for each year in advance taking into account the state of the groundwater reservoir at the beginning of the pumping season. However, for technical reasons, this ideal scheme of operation can be put into effect only gradually. The basic safety rule had to be relaxed during the last two years, the spring was left dry in summer and only the general pattern of the potential distribution in the aquifer was preserved. Forecasts of the strongly reduced discharge of the spring were worked out on a monthly basis and proved quite reliable. In particular the date of cessation of spring discharge was forecast within the margin of a fortnight.

The yearly water balance of the aquifer was established by first calculating the groundwater reservoir of autumn 1954 from the records of undisturbed spring discharge 1949/1950 — 1953/1954. From 1954/1955 onwards pumpage became increasingly felt and corrections for dynamic effects had to be applied. These corrections are comparatively small in the spring months March-April from which the yearly maximum reservoir is calculated. Therefore calculations were based on the yearly interval April to April rather than on the customary hydrological year which is reckoned from October to October. Results are shown in the folowing table. Cessation of spring flow which is due to depletion of the reservoir and dynamic influences indicates the essential correctness of the calculations.

REFERENCES

(1) S. Mandel and F. Arad, Geo-hydrology of Western Galilee, „TAHAL", Tel Aviv, 1958 (Hebrew).

(2) K. Taussig, Natural groups of groundwater and their origin. Mekoroth Water Co. Ltd., Tel Aviv, 1961.

(3) F. Mero, Hydrological investigation of the Na'aman spring region, „TAHAL", Tel Aviv, 1958.

TABLE 1

Water balance of the Na'aman aquifer

Year	October Volume MCM	Rain mm.	Maximum spring discharge		Maximum Volume Calculated MCM	Yearly Yield		
			Gauged cu. m/sec	*Corrected cu. m/sec		Spring MCM	Wells MCM	Total MCM
1953/1954	168	696	2.09	2.20	222	49.1	3.9	53.0
1954/1955		390	2.08	2.20	171	35.8	9.4	45.2
1955/1956		697	1.72	1.77	180	35.3	17.6	52.9
1956/1957		492	1.45	1.50	153	24.8	22.7	47.5
1957/1958		621	**	1.38	140	28.6	25.5	54.1
1958/1959		510	0.88	1.07	109	13.9	27.6	41.5
1959/1960		475	0.53	0.73	74	5.8	24.7	30.5

** Maximum spring flows of as much as 1.81 cu. m./sec. were measured, however these seem to be due to physical disturbances caused by extremely heavy rainfall. The correlated maximum flow was actually computed from subsequent observations.

*Corrections applied for dynamic influences of simultaneous pumpage in wells, see text.

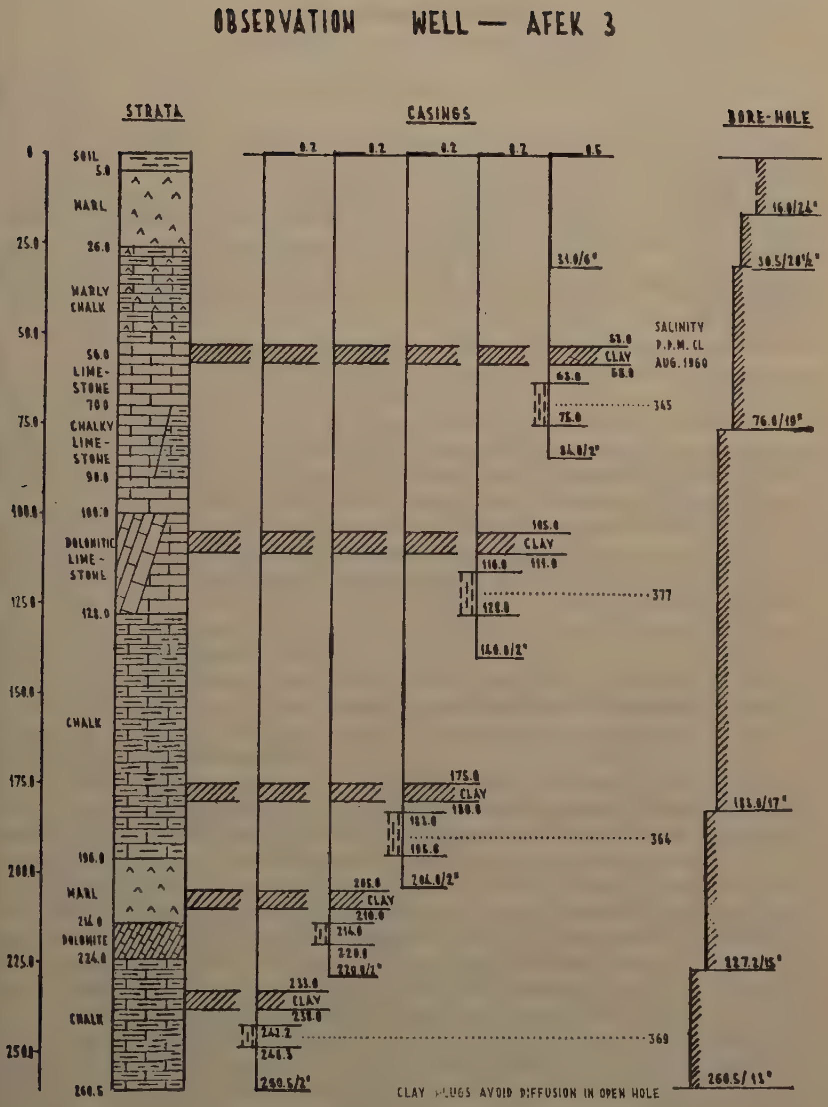

OBSERVATION WELL — AFEK 3
STRATA
CASINGS
BORE-HOLE
0
25.0
50.0
75.0
100.0
125.0
150.0
175.0
200.0
225.0
250.0
SOIL
5.0
MARL
26.0
MARLY CHALK
56.0
LIME-STONE
70.0
CHALKY LIME-STONE
90.0
100.0
DOLOMITIC LIME-STONE
128.0
CHALK
196.0
MARL
214.0
DOLOMITE
224.0
CHALK
260.5
0.2
0.2
0.2
0.2
0.5
34.0/6"
53.0
CLAY
58.0
63.0
345
75.0
84.0/2"
SALINITY P.P.M. CL AUG. 1960
105.0
CLAY
110.0
114.0
377
128.0
140.0/2"
175.0
CLAY
180.0
183.0
364
195.0
204.0/2"
205.0
CLAY
210.0
214.0
220.0
229.0/2"
233.0
CLAY
238.0
242.2
369
246.5
260.5/2"
16.0/24"
30.5/20½"
76.0/19"
183.0/17"
227.2/15"
260.5/13"
CLAY PLUGS AVOID DIFFUSION IN OPEN HOLE

Fig. 3

TABLE 2

Chemical Analyses (By Courtesy of Mr. K. Taussig, Mekoroth Water Co. Ltd.)

			Ions: mg/l.				
	Cl	SO_4	NO_3	HCO_3	Ca	Mg	Na
Well Damun 3	127.6	19.1	17.7	371.9	91.0	35.3	67.5
Na'aman Spring	628.3	87.2	7.1	387.1	114.2	66.8	340.6
Well Kefar Masaryk	1,090.3	44.9	3.5	388.6	131.9	89.8	612.2
Mediterranean Sea Water	21,983	3,130	3.1	110.7	508.2	1,514	12,372

RELATIONS ENTRE LA COMPOSITION CHIMIQUE DES SOURCES THERMOMINÉRALES EN GRÈCE ET LA CONSTITUTION GEOLOGIQUE DU PAYS

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Résumé

Après un bref apercu de l'histoire géologique de la Grèce et du démembrement du sol hellénique, l'ecrivain explique la composition chimique si variée des sources minérales par rapport à la formation géologique du district où elles jaillissent.

Certains faits dont l'interprétation était difficile ont trouvé dans la suite leur explication après une recherche géologique détaillée de la part de géologues.

L'étude systématique des sources thermominérales de Grèce du point de vue chimique et physico-chimique ont permis de longues observations sur leurs effets curatifs et ont eu comme résultat la construction d'installations balnéaires modernes dans certaines d'entre elles.

Comme il est bien connu la Grèce constitue au point de vue géologique une des contrées les plus jeunes de notre continent.

Un court aperçu sur son évolution tectonique nous aiderait à comprendre la richesse, la diversité et la distribution géographique des ses sources thermominérales:

Pendant les longs siècles qui se sont écoulés jusqu'à la fin de la période secondaire, c'est-à-dire pendant un intervalle qui représente plus de neuf dixièmes du temps passé depuis le dépôt des premières couches sédimentaires jusqu'à l'époque actuelle, la région de la Grèce formait un fond marin, sur lequel se déposaient et se stratifiaient des calcaires, des schistes argileux et des grès.

C'est durant la période tertiire et précisèment après le plaléogène que la Grèce émergea de la mer, par suite des grands plissements de l'écore terrestre, connus sous le nom de plissements alpins.

La terre ainsi formée s'étendait unie vers le sud jusqu'au delà de l'île de Crète, et depuis les îles Ioniennes jusqu'à la partie occidentale de l'Asie Mineure. En géologie on appelle cette terre Egéide, car sa partie centrale couvrait alors toute l'étendue que la mer Égée occupe aujourd'hui.

L'Égéide constitue une partie des chaînes de montagnes qui se ramifiant des Alpes orientales descendent vers le sud avec une direction sud-sud-estet puis tournent vers l'est et s'unissent avec les chaînes de montagnes de l'Asie Mineure. Cette chaîne formant l'Égéide est connue en géologie sous le nom des Alpes Dinariques.

Vers la fin de la période tertiaire, l'Égéide a subi de grandes déformations. Elles sont dues principalement à des nombreuses fractures et à des effondrements qui ont provoqué entre autres la formation des golfes et le démembrement du sol hellénique.

La déformation s'accentua pendant la période quaternaire par suite de l'ennoyage progressif de la terre qui forme aujourd'hui le fond de la mer Egée.

Un autre événement d'une importance capitale pour notre sujet fut l'activité volcanique intense qui s'est manifestée le long de certaines fractures tectoniques et dans les zones des effondrements. L'activité volcanique est d'ailleurs le dernier terme de la série des phénomènes constituant la phase d'orogénèse.

Les volcans apparus sont nombreux et se trouvent tous dans l'Égéide centrale. Quelques-uns d'entre eux sont encore en activité intermittente, comme ceux des îles Santorin et Nisyros. Un autre, le volcan de Méthana, a été en activité pendant les temps historiques. Le volcan de Soussaki se trouve actuellement dans sa phase de mofette, tandis qu'une solfatare est le dernier vestige actif du volcan de l'île de Milo.

Les étendues couvertes par les laves des volcans de l'Égéide sont plutôt restreintes, excepté celles de la Thrace occidentale et de l'île de Mételin.

Après ce bref exposé sur la structure géologique de la Grèce on comprend aisément pourquoi le sol hellénique, qui a été fracturé par des failles étendues et profondes et qui fut le théâtre d'un volcanisme de période récente, est doté par la nature d'une abondance de sources thermominérales.

Comme il est naturel, la composition chimique de chaque source est intimement liée à la constitution géologique de la région avoisinante. La composition chimique des sources minérales situées près de la mer est en outre plus ou moins influencée par les infiltrations marines. C'est ainsi qu'en Grèce les sources thermominérales côtières, en dehors de leurs autres constituants contiennent une quantité de chlorure de sodium de 1 à 29 grammes par kilogramme d'eau.

Nous allons maintenant traiter la répartition géographique des sources thermales en Grèce, en rapport avec la constitution géologique du pays.

Une catégorie spéciale de sources apparaît en Grèce occidentale parallèlement aux Alpes Dinariques depuis l'Épire jusqu'au sud du Péloponnèse. Ce sont les sources de la zone qui s'étend le long de la côte Ionienne. Cette région est caractérisée par l'absence de toute manifestation volcanique et par la présence d'assez étendues couches de gypse. Dans plusieurs endroits il y a aussi apparition d'asphaltes.

C'est un cas des plus typiques de la relation qui existe généralement entre les plissements de l'écorce terrestre et les dépôts lagunaires; car c'est par l'effet de ces plissements que se sont constitués les bassins d'évaporation, où se sont déposées les couches de gypse.

Toutes les sources de cette zone appartiennent à la catégorie des sulfhydriques ou à celle mixte des sulfhydriques — sulfatées calciques-chlorurées sodiques. Elles contiennent plutôt de petites quantités de bicarbonates et d'acide carbonique libre et leurs tempétatures ne dépassent pas 36°C.

La plus importante d'entre elles est la source de Kaïapha au Péloponnèse, qui évidemment doit sa génèse à la fracture bordière de la mer Ionienne, sur laquelle d'ailleurs elle émerge.

Elle rentre dans la catégorie mixte nommée précédemment et se distingue par la grande quantité d'acide sulfhydrique libre qu'elle contient (0,05 gram. par kilogr. d'eau). Sa température est de 36° C. Son griffon se trouve au fond d'une grotte spacieuse, que l'écrivain de l'époque hellénistique Pausanias mentionne déjà sous le nom de grotte des nymphes Anigrides. Cette grotte constitue une excellente salle d'inhalation naturelle, car son atmosphère contient en proportion convenable l'acide sulfhydrique exhalé par l'eau ainsi que les produits de son oxydation.

Une autre source importance de la même zone est la source de Cyllène, située aussi à la côte occidentale du Péloponnèse. Elle est sulfhydrique- chlorurée sodique, d'une température de 25° C. Sa renommée pour ses effets curatifs contre les affections des organes de la voie respiratoire est très répandue. Elle est fréquentée surtout par les asthmatiques.

Les composés sulfureux des sources de la zone Ionienne doivent leur provenance à la réduction par des matières organiques ou des bactéries du gypse, qui se trouve non seulement en couches distinctes, mais aussi disséminé dans le flysch et dans le néogène.

Une source de cette catégorie fait aussi son apparition dans l'île de Crète (département d'Héraklion) près du village de Plouti. L'île de Crète est bien connue pour ses dépôts de gypse.

Il en est de même pour deux autres thermes sulfureuses situées aux confins de Thessalie et de Phtiotide: celles de Smokovo et de Platystomo. Elles émergent dans le flysch et leurs températures sont respectivement de 40° C et de 33° C. Les eaux de ces sources ont une faible minéralisation, vu que leurs eaux circulent dans du flysch constitué pour la plupart de grès, sont totalement dépourvues d'acide carbonique libre et possèdent, par suite de la présence d'ions carbonates, une réaction nettement alcaline vis-à-vis de la phénolophtaléine. Leur pH est compris entre 9 et 10; elles appartiennent par conséquent à la rare catégorie des sources sulfureuses — réellement alcalines.

Des bulles de gaz combustibles (constitués pour la plupart de méthane) émergent des eaux de ces sources. Elles rappellent en beaucoup de points les eaux sulfureuses réellement alcalines de quelques sources chaudes des Pyrénées, comme Cauterets ($p_H = 9,4$), Barèges ($p_H = 9,9$) et Bagnères de Luchon ($p_H = 8,9$).

Beaucoup d'autres thermes sulfureuses existent en Grèce, qui doivent l'origine de leurs sulfures à des sulfates ou à des sulfures métalliques et spécialement à des pyrites. Telles sont en Chalcidique la source de Nea Apollonia (49° C) en Thrace occidentale la source de Ferrai (50° C), en Phtiotide les sources de Hypati (33° C) de Thermopylai (32°) et de Koniaviti (33°) pour ne citer que celles qui ont un grand débit et qui sont en exploitation.

Sur quelques unes d'entre elles nous reviendrons à cause de l'importance de leur composition chimique.

A l'encontre des sources sulfureuses précédentes il y en a d'autres dont les sulfures ont une provenance volcanique. Telles sont les sources importantes du volcan éteint de Méthana, dans le golfe Saronique.

Elles sont des sulfureuses-chlorurées sodiques fortes, riches en acide carbonique libre, d'une température de 34° C. Elles proviennent évidemment d'infiltrations d'eau de mer, qui se charge en son cours souterrain par les gaz acide sulfhydrique et acide carbonique, dégagés du foyer du volcan éteint.

Ces sources émergent au bord de la mer, dans le calcaire néocrétacé, tout près du contact de ces roches avec les laves dacitiques du volcan et alimentent le grand Etablissement balnéaire. Elles présentent le phénomène connu de la pulsation, qui consiste en une fluctuation de leur débit, et qui est dû à une irrégularité de la quantité des gaz exhalés par le magna du foyer volcanique, qui se trouve dans la période de refroidissement.

Il est à remarquer qu'à une distance de un kilomètre de ces sources sulfureuses jaillit dans la roche éruptive même et au bord aussi de la mer, une autre sourcre totalement dépourvue de sulfures.

Elle est chlorurée sodique, assez chargée d'acide carbonique libre (0,6 gr. par kilogr. d'eau) et d'une température de 41°C.

Par le fait du manque de composés sulfureux dans cette dernière on ne peut pas contester la provenance volcanique des sulfures des sources précédentes, car à d'autres points du volcan émergent aussi des thermes sulfureuses et fonctionnent de fumérolles exhalant de l'acide sulfhydrique.

Dans les autres centres volcaniques en Grèce, qui pourtant sont assez nombreux, il n'y a pas de thermes sulfureuses importantes. Par contre il y a beuacoup de chlorurées sodiques, surtout dans l'île de Métélin.

Cette île, dont une grande partie est formée par des roches volcaniques (andésites) possède des sources thermales à Polychnitos, à Thermi, à Efthalou (près de Molyvo) et à Saint Jean de Lisborion, pour ne citer que les plus importantes. Toutes émergent à proximité du rivage. Les deux sources de Polychnitos d'une température de 76° et de 81° C se distinguent par leur grand débit total (1400 mètres cubes par 24 heures) et aussi par une quantité importante d'ion lithium qu'elles contiennent (6 milgr. par kilog. d'eau). De même riche en lithium est la source de Thermi, qui est une ferrugineuse-chlorurée sodique forte, d'une température de 47° C. La source d'Efthalou (46°C) qui se trouve près d'une mine de galène possède une radioactivité de 15 unités Mache.

Les gaz qui se dégagent à travers l'eau de cette source ont une radioactivité de 180 unités Mache (par 1000 c.c. sous conditions normales).

Les sources thermales qui se trouvent dans d'autres centres volcaniques (Santorin, Milos, Limnos, Samothrace, Aegina, Nisyros) sont d'une moindre importance.

En dehors de Métélin, deux autres îles dans la mer Égée du sud disposent de sources thermominérales importantes. Ce sont Kythnos et Nikaria, qui appartiennent au massif crystallophyllien, avec apparition de nombreuses éruptions de granite. Kythnos, en dehors de ses sources est connue pour ses minerais de fer, qui sont depuis longtemps en exploitation. Ses sources thermales sont au nombre de deux. L'une, d'une température de 52° C est ferrugineuse- chlorurée sodique - radioactive (25 unités Mache). C'est à Kythnos que l'on a érigé les premières installations balnéaires après l'Indépendance de l'Etat Héllénique (1827).

Nikaria est constituée en grande partie par du granite. Ses sources, dont les plus importantes sont au nombre de six, émergent du côté sud et du côté nord-est de l'île. Leur température est comprise entre 33° et 58° C. Elles sont toutes chlorurées sodiques et trois d'entre elles sont fortement radioactives. Leur radioactivité, qui est, la plus haute mesurée jusqu'à présent en Gréce, est comprise entre 320 et 760 unités Mache. Les trois autres ont une radioactivité de 6 à 80 unités Mache.

Comme le prouve la courbe de désonance de l'activité induite, la radioactivité des differentes sources en Grèce est due à du radon (émanation de radium). Les résultats cités en unités Mache se rapportent à la seule émanation contenue dans l'eau ou les gaz, car le surcroît de radioactivité, provenant de l'activité induite, a toujours été soustrait.

Comme il est bien connu, plusieurs sources thermales émergent souvent sur différents points de la même faille, constituant ainsi les nommées *lignes de thermes*. Une telle ligne forme les sources précédemment nommées de Hypati, Thermopylai et Coniaviti en Phtiotide. Elles ont presque la même température de 33° C et appartiennent à la même catégorie des sulfureuses — chlorurées sodiques- bicarbonatées alcalinoterreuses. Elles sont aussi plus ou moins chargées d'acide carbonique libre. Le débit de chacune d'elles dépasse les 1200 mètres cubes par 24 heures. La plus fameuse d'entre elles pour ses effets curatifs est celle de Hypati, qui est la plus riche en acide carbonique libre, (1,5 gram. par Kilogr. d'eau). Au griffon de cette source se dégagent à travers l'eau de grandes quantités de gaz, constitués en 95% d'acide carbonique et évalués à 500 mètres cubes par 24 heures.

Au prolongement de cette ligne de thermes du côté de l'ile d'Eubée et sur le rivage de cette île il y a deux centres hydrothermaux, ceux d'Aedipsos et de Gialta. Leur emplacement se trouve au croisement des failles qui ont donné naissance aux golfes Maliaque et Euboique. La connexité des ces fractures d'effondrement avec les phénomènes volcaniques est marquée par la présence, sur ce croisement, des îles Lichades, constituées par les laves d'une éruption sous-marine.

Les sources d'Aedipsos, qui étaient en grande réputation depuis l'époque romaine, émergent à la proximité d'une éruption de granulite et sont extrêmement nombreuses Elles ont un débit total évalué à plus de 5.000 mètres cubes par 24 heures et appartiennent à la classe mixte de chlorurées sodiques fortes- bicarbonatées alcalinoterreuses. La température des plus importantes d'entre elles est comprise entre 50° et 79° C. Ces sources occupent une superficie de 30 hectares et déposent à leurs points d'émergence des masses puissantes de carbonate de chaux rougeâtre, qui servent par endroits comme carrières. Les édifices de la ville d'eau d'Aedipsos, les quais etc. sont bâtis avec des moellons provenant de ces carrières.

Ces eaux ont une vieille réputation dans le traitement des rhumatismes arthralgiques, des névralgies tenaces comme la sciatique et des traumatismes ostéo-articulaires. Le nombre des bains donnés chaque saison dans les Établissements balnéaires d'Aepsos dépasse 150.000.

Les deux sources de Gialta, d'une température de 44° C, ont une composition chimique semblable à celle des sources avoisinantes d'Aedipsos. La plus abondante d'entre elles (700 mètres cubes par 24 heures) a jailli à la suite d'un tremblement de terre intense, advenu en 1894.

Sur le même croisement des failles, mais sur la côte de la Grèce continentale, en Locride, se trouvent les sources chlorurées sodiques radioactives de Kaména Vourla, dont le débit total s'élève à 1300 mètres cubes par 24 heures. Les eaux de l'ensemble des sources, avec une température de 37° C et une radioactivité de 180 unités Mache, alimentent un grand Établissement balnéaire moderne. La radioactivité des gaz qui s'échappent à travers l'eau aux griffons s'élève à 1130 unités Mache par 1000 cc. mesurés sous conditions normales.

Au voisinage des sources minérales il y a une source froide d'eau potable, ayant un débit important et une radioactivité de 85 unités Mache.

Kaména Vourla est un exemple de ville d'eau qui en très peu d'années, s'est développée en une Station balnéaire de tout premier ordre, grâce aux qualités exceptionnelles de ses eaux et aussi grâce aux beautés naturelles de son site.

Une autre région fracturée par des failles en escalier, cheminant parallèlement sur une grande longueur, est celle comprise entre le golfe de Corinthe et le golfe Saronique. Là , et précisément au fond du golfe de Corinthe se trouvent les sources de Loutraki. Elles ont un grand débit, une température de 32° C et rentrent dans la catégorie des chlorurées sodiques faibles. Bien que la cure soit avant tout une cure de boisson, Loutraki possède un Établissement de bains moderne et deux autres qui utilisent l'eau minérale tiède naturelle. Il dispose aussi d'une installation d'embouteillage aseptique et automatique. Les eaux ont une radioactivité de 10 unités Mache.

Loutraki est la station la plus renommée de diurèse en Grèce. Ses eaux sont indiquées contre la diathèse urique, la gravelle, la lithiase rénale, les pyélonéphrites, les cystites etc.

Jusqu'à présent nous avons mentionné des sources chlorurées sodiques fortes ou faibles et des sources sulfureuses, ainsi que leurs combinaisons avec des sulfatées calciques, ferrugineuses, carbogazeuses, alcalinoterreuses et radioactives.

Les sources minérales des autres catégories ne manquent pas pourtant en Grèce, quoique elles se rencontrent, en moindre proportion.

Ainsi en Macédoine dans le bassin de Langaza, qui constitue un fossé tectonique dans les couches crystallophylliennes, émergent (à une distance de 18 Kilomètres environ au NE de la ville de Salonique) des sources simplement thermales, dites aussi sources alpestres, d'une température de 39° C et d'un débit de 1250 mètres cubes par 24 heures.

Leur minéralisation est moindre d'un gramme par kilogramme d'eau. Les sources thermales viennent au jour à travers une des failles qui ont occasionné la formation du bassin tout entier de Langaza.

La station de Langaza dispose d'installations balnéaires modernes et elle est parmi les plus fréquentées surtout der les habitants de la Macédoine.

A l'est de Langaza se trouve l'étendue vallée de Serrai, dont la formation est identique à celle du bassin de Langaza. C'est sur une des failles bordières de cette vallée, près de la ville de Nigrita qu' émergent les sources du même nom.

Elles sont alcalines-alcalinoterreuses-carbogazeuses, d'une température de 56° C. Non loin des sources chaudes il y a une source de 24° C, d'eau potable bicarbonatée mixte-carbogazeuse. Cette eau dont la composition chimique ressemble à celle de Vichy en France est embouteillée et expédiée en assez grande quantité.

Sur le prolongement de la même faille qui donne naissance aux sources de Nigrita, et qui a une direction nord ouest-sud est, sourdent les thermes d'Elefterai en Thrace occidentale. Elles sont situées à un kilomètre de la côte, ont un débit important et une température de 41° C.

Ainsi que les sources de Nigrita elles sont bicarbonatées mixtes-carbogazeuses, mais comme elles se trouvent à une petite distance de la mer elles sont en outre légèrement chlorurées sodiques. Près du lieu des sources et en plusieurs endroits s'exhale du gaz acide carbonique par des petites fissures du sol. Malgré l'importance des eaux au point de vue de la composition chimique, la Station d'Elèfterai, ayant un accès plutôt difficile, a une clientèle restreinte.

Outre les stations déjà nommées de Langaza et de Nigrita, il y a en Macédoine deux stations thermales importantes, celles de Sidirokastron et de Ardea.

Les sources de Sidirokastron: d'une température de 44° C sont bicarbonatées mixtes-carbogazeuses. Elles se trouvent, comme celles de Nigrita, au bord de la vallée de Serrai et à une distance de 5 kilomètres au nord-ouest de la ville de Sidirokastron. A la ville d'eau qui dispose de bonnes communications on donnait plus de 27.000 bains par saison avant la dernière guerre.

La station thermale de Ardea, située près des confins Greco-Yougoslaves, à une altitude de 460 mètres, dispose de plusieurs sources, dont la plus chaude et la plus abondante en même temps, a une température de 45° C. Les eaux appartiennent à la catégorie des bicarbonatées alcalinoterreuses.

Comme le prouvent les ruines d'installations balnéaires, Ardéa était déjà une station thermale à l'époque de l'empire byzantin.

Presqu'à la même altitude que celle de Ardéa est située la ville d'eau déjà mentionnée de Smokovo en Thessalie. Toutes les autres stations thermales sont situées à une altitude moindre.

En Grèce la plupart des sources minérales jaillissent près des côtes de la mer ou aux versants des montagnes; très peu d'entre elles sont situées au fond de vallées ou encaissées dans des vallons. Ainsi les villes d'eau jouissent d'une vue étendue et agréable, chose qui exerce une action bienfaisante sur le moral des patients nerveux et mélancoliques.

En dehors des sources thermominérales déjà mentionnées, et qui ont été l'objet d'une étude minutieuse au point de vue de leur composition chimique, il y a en Grèce un assez grand nombre d'autres, qui ne sont pas exploitées jusqu'à présent, ou qui sont d'une importance régionale. Plusieurs d'entre elles ont un grand débit et une température assez élevée. Parmi les grands départements seule l'île de Crète ne dispose de source thermominerales, excepté celle déjà mentionnée de Plouti. Par contre on y rencontre des sources minérales froides, dont quelques unes sont employées en cure de boisson.

Des sources minérales froides employées exclusivement en boisson, il y en a plusieurs en Grèce, dont les plus renommées sont a Cerigo (ferrugineuses), à Tsagesi en Thessalie (ferrugineuses–carbogazeuses) à Xyno Nero en Macédoine (bicarbonatées alcalinoterreuses–carbogazeuses) et à Souroti en Chalcidique (bicarbonatée–alcalinoterreuse–carbogazeuse). A Xyno Nero et à Souroti il y a des installations complètes d'embouteillage de l'eau.

Nous avons déjà dit que l'eau des sources chlorurées sodiques fortes en Grèce provient en grande partie d'infiltrations marines. Chez nous il n'y a pas de sources chlorurées sodiques fortes dont la teneur en ion chlore dépasse celle de l'eau de la mer. Il est à remarquer que dans toutes ces sources le rapport de la teneur en ion magnésium par la teneur en ion chlore est toujours moindre que dans l'eau de mer.

Cela peut être expliqué par des phénomènes de diagénèse et principalement par la dolomitisation des calcaires rencontrés par les eaux des sources à leur cours souterrain, comme aussi par la formation de silicates de magnésium d'origine hydro-thermale (diopside).

TECHNIQUES OF GROUND WATER DEVELOPMENT IN THE NAVAJO COUNTRY: ARIZONA, NEW MEXICO, AND UTAH, U.S.A.

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ABSTRACT

The Navajo country, a high tableland, has a cool climate and arid environment—the region is 50 percent desert. It lies at a mean altitude of 5,500 feet and consists of alluvial valleys, rolling plains, mesas, buttes, incised canyons, and dispersed mountains. A thin mantle of soil, sparse grass, and scarcity of water have been ever-urgent problems in sustaining a productive and self-sufficient economy.

The objectives for ground water development in the Navajo region were to: 1) Provide permanent water supplies; 2) assure sufficient potable water for domestic, stock and institutional needs; 3) ascertain if water could be developed for industry and irrigation.

The streamflow is small and intermittent, as much precipitation is lost to evapotranspiration. Early ground water development by shallow alluvial wells was subject to failure in drought periods. Methods of attack to determine the occurrence of ground water included: 1) Differentiation of the sedimentary rocks and mapping their lateral and vertical distribution; 2) measurement of water levels, saturated thickness, well yield, and quality of water; 3) correlation of data from test-wells with regional studies.

Significant factors of the region are the occurrence of eight, finegrained water-bearing formations that yield small to moderate amounts of water to wells, ranging in depth from 50 to 2,000 feet. Although large amounts of water are in storage, the low permeability will not permit large yields but adequate amounts can be produced in most places. In specific areas, water for industry and irrigation can be developed; in other areas water is beyond practical reach or unfit for use.

RÉSUMÉ

La région de Navajo, un plateau élevé, a une climat froid et elle se trouve dans une région aride (50 % désertique). Elle se trouve à une altitude moyenne de 5500 pieds et elle comprend des vallées alluviales, des plaines ondulées des collines, des canyons et des montagnes dispersées. Un manteau peu épais de sol, des herbages épars et la rareté de l'eau constituent des problèmes urgents pour lui permettre de vivre sur elle-même.

Les objectifs du développement de l'eau souterraine dans la région de Navajo étaient : 1) d'assurer des ressources permanentes en eau; 2) d'assurer assez d'eau potable; 3) de rechercher si les ressources étaient suffisantes pour l'industrie et l'irrigation.

L'écoulement des rivières est faible et intermittent, car une part trop grande des précipitations en perdue par évapo-transpiration. Le développement antérieur des ressources en eau souteraine par des puits peu profonds était insuffisant en période de sécheresse. Les méthodes utilisées pour rechercher l'eau souterraine comprenaient : 1) Différentiation des roches sédimentaires avec cartographie de leur distribution verticale et latérale; 2) mesure des niveau d'eau, de l'épaisseur saturée, des débits des puits, de la qualité de l'eau; 3) corrélation des résultats de pompages avec des études régionales. Un facteur important pour la région était l'existence de huit couches aquifères, finement granulées, avec des débits faibles ou modérés s'étageant à des profondeurs de 50 à 2000 pieds. Bien que d'énorme quantité d'eau existaient, la faible perméabilité ne permet pas des débits importants mais des montants adéquats peuvent être obtenus en beaucoup d'endroits. En certains endroits de l'eau pour l'industrie et l'irrigation peut être obtenue. En d'autres régions, l'eau est pratiquement hors d'atteinte ou non utilisable.

1. PHYSICAL AND ECONOMIC FEATURES

The scarcity of water in the Navajo country is a dominating factor in everyday life of the Navajo and Hopi people. Many families still haul domestic water as much as ten miles and drive livestock even further for water. Small perennial streams and springs are widely scattered in this region and furnish limited water supplies. In many places, the ground water is not suitable for consumption by man or livestock nor is it available within practical reach of drilled wells.

The Navajo country lies in the southwestern part of the Colorado Plateaus physiographic province in the Rocky Mountain region of United States. The region considered herein lies within the Colorado River drainage basin and is bounded by two principal tributaries; San Juan River on the north and the Little Colorado River on the south. Also, it is a principal part of Arizona's Plateau Uplands water province (fig. 1) which includes many mesas, buttes, gently sloping mountains, and deeply incised canyons. The altitude ranges from 4,000 to 10,000 feet above sea level. The cover of vegetation on the gently sloping surfaces is sparse and is supported by a thin soil mantle and scanty precipitation.

Nearly all the perennial streams originate in the high mountainous areas and drain into the Little Colorado River (fig. 1). Runoff from snowmelts helps prolong streamflow in the spring, but most of the washes are dry and flow only after thunderstorms during July and August. Streams from the mountains fan out in broad, braided channels, where water sinks into the alluvial material, only to be pulled back to the atmosphere by evapotranspiration. These intermittent streams yield very little water in proportion to the size of their drainage area.

The rock formations in the Navajo country include sandstone, siltstone, mudstone, claystone, and limestone. The sandstone sequences are capable of storing and transmitting water and are the potential source of ground water. The claystone and siltstone are sensibly impermeable to water; these are the confining media which hydraulically separate the water-bearing formations (fig. 2). Thus, the potentiality of ground-water yield at any site depends on an interplay between variable geologic and hydrologic factors and must be unraveled by the application of geohydrologic techniques.

The need for adequate water supplies for the Navajo and Hopi people prompted the Bureau of Indian Affairs to request the U.S. Geological Survey to undertake a comprehensive study of the ground-water resources of the Navajo country in 1950. During this study, the U.S. Geological Survey furnished technical assistance for the development of about 300 water wells. In parts of the region wells that produce as little as 500 to 1,000 gallons of water per day are considered successful because they are the only source of water for Indian inhabitants and their livestock.

In the past years the Navajo people lived a mobile pastoral life, moving from one place to another with seasonal changes, seeking better grazing lands and adequate water for support of their meager crops and livestock. The Hopi people choose to live in communities even though water is not plentiful. The main occupations of the Indian people within the reservation are raising livestock, farming small plots, arts and crafts, and extraction of natural resources. Many of the necessities of life are obtained by exchange of goods so that trading is a dominant economic activity.

At present the expanding economy in the Navajo country is creating an unprecedented demand for stock, domestic, municipal and industrial water. For example, a forest-products processing plant requiring a total of 1.5 mgd (million gallons per day) of water is being built by the Navajo Tribe. Water needs for the tribal and government headquarters, community of Window Rock, have doubled in the last 3 years. Exploration and development of petroleum in the northeastern part of the region in the past 5 years have also contributed to the new Indian economy. As a result the standard of has been raised with a corresponding increase in water requirements.

The Navajo country contains much wealth in natural resources including water reserves. As in the development for all natural resources an understanding of the occurrence and geometric framework of the storage reservoir are fundamental requi-

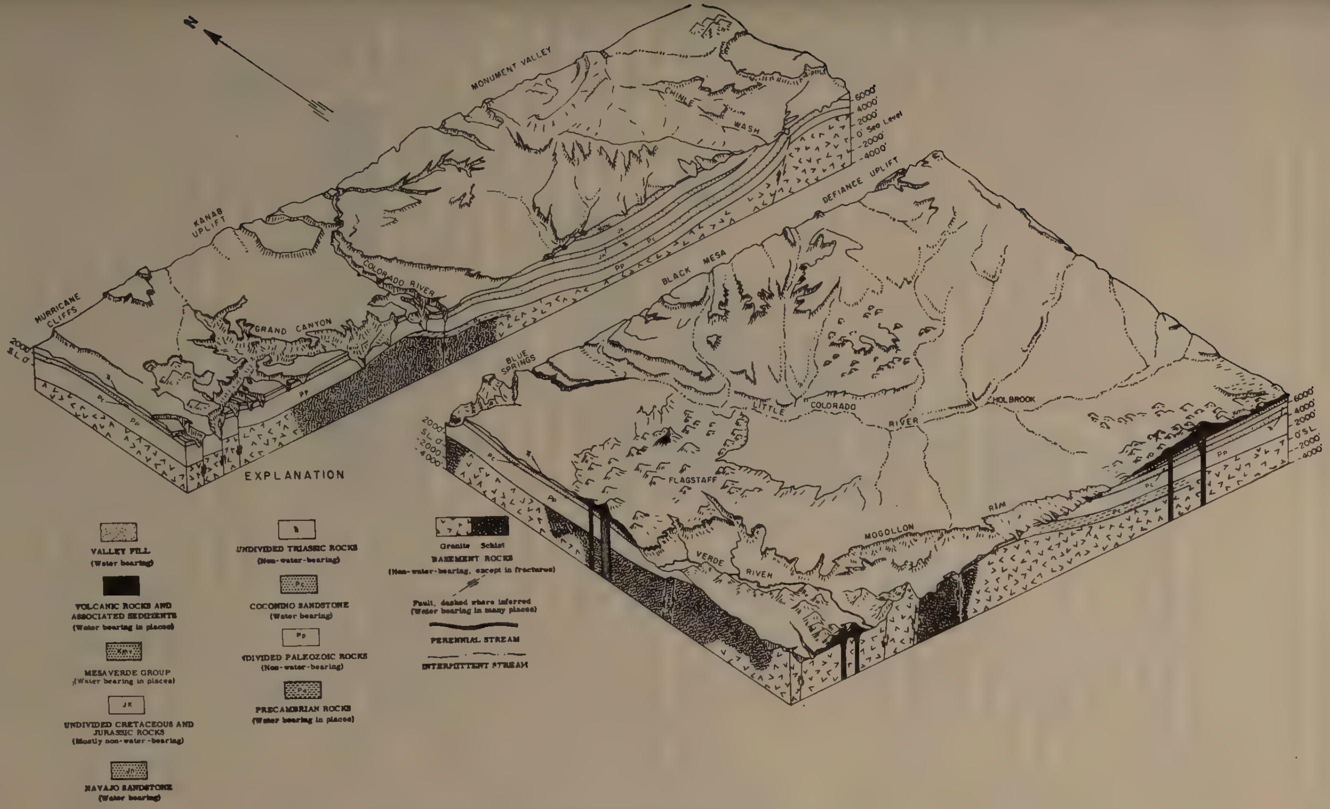

Fig. 1 — Plateau Uplands Water Province.

sites. Because water is a transitory resource, realistic knowledge of the behavior of movement and geologic controls is essential for intelligent exploration and exploitation.

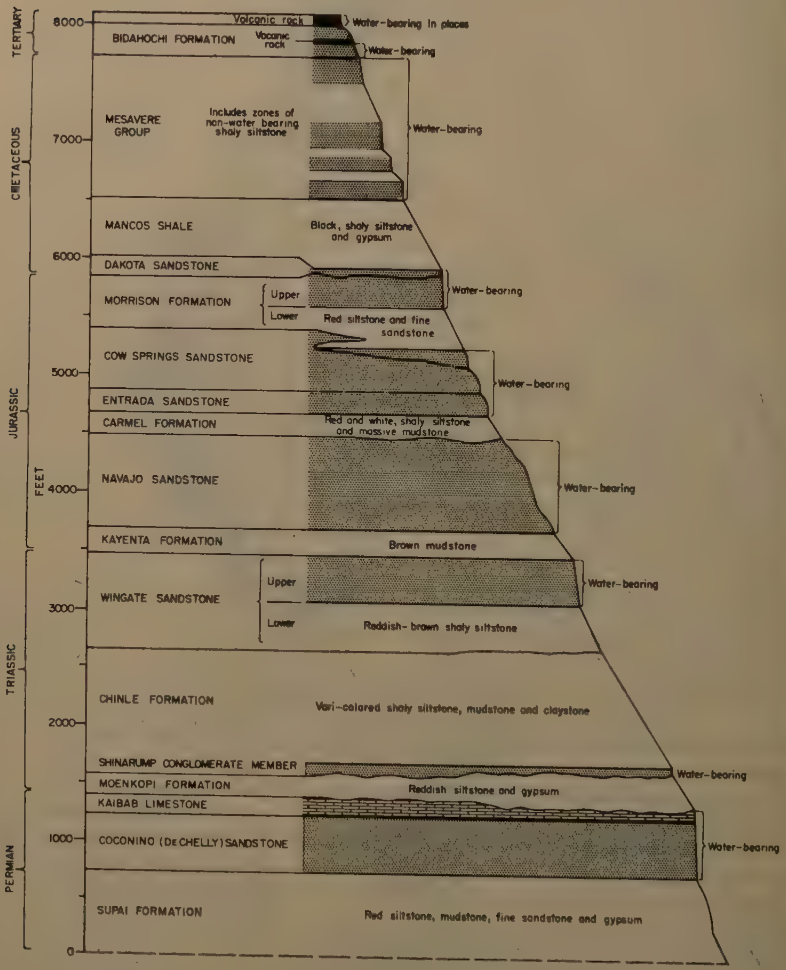

Fig. 2 — Rock Formations in the Navajo country.

2. TECHNIQUES FOR DETERMINING THE OCCURRENCE AND AVAILABILITY OF WATER IN SANDSTONE AQUIFERS

The initial technical assistance furnished by the U.S. Geological Survey for development of ground water supplies consisted of feasibility studies for groundwater development at specific sites. These required field reconnaissance to determine the occurrence of water in certain stratigraphic units and to estimate the chemical quality of the water. As adequate geologic and stratigraphic information were lacking, considerable work was essential to prepare tenable conclusions for proposed well developments. The Geological Survey assistance drew heavily upon the drillers' logs of scattered drilled wells in the region and the projection of this information at the desired site. Although this assistance resulted in the development of several successful wells, it became apparent that comprehensive geohydrologic studies were necessary to supply the needed information for the large well development envisioned. Because the major aquifers in the Navajo country consist mostly of fine-grained terrestrial sediments, including many facies changes and a heterogeneous complex of stratal units, detailed stratigraphic studies were essential to unravel the vertical and lateral distribution of potential water-bearing zones. In 1951 the regional geologic and hydrologic studies were initiated to provide basic information to determine the occurrence and availability of water development.

2.1. *Stratigraphic Studies and Geologic Mapping Methods*

A reconnaissance examination of the rocks that might be potential aquifers in the Navajo country indicated that stratigraphic studies of the Jurassic rocks would provide expedient results. Detailed stratigraphic sections were measured at strategic points throughout the area. Rock samples were collected from the outcrops for laboratory analyses, including particle size analyses and heavy mineral determinations. Data was collected on sedimentary structures and fossil evidence were used to ascertain the paleo-environments and mode of deposition. Detailed geologic mapping accompanied the stratigraphic work in order to determine the areal extent of the potential sandstone aquifers and the spatial relations of interfingering and gradational features.

Field descriptions of the stratigraphic sections included examination of physical properties such as grain size, color, cement, composition, bedding, fossils, surface marks, relation to adjacent units, structural attitude, and thickness of strata. Color of rocks was determined by use of a standard rock color chart as distributed by the National Research Council. Grain size in the field was made by comparison with samples of standard sizes attached to cards or encased in plastic holders. Degree of sorting were estimated and composition determinations were limited to identification with handlens. Bedding features were classified and recorded in a uniform procedure. The grain size and rock names used were standardized according to the Wentworth classification.

Because many of the sandstone units were potential water-bearing formations particular emphasis was made on the crossbedding features for differentiation and correlation purposes. Crossbedding was classified into three main types; simple, planar, and trough. The distinguishing characteristics of these types are exhibited by the external features of an individual oriented group of crossbeds. In this study the characteristics of the individual crossbeds typical of the group were classified as follows: 1) Concave or convex (upward); 2) high (more than 20 degrees) or low angle of dip; 3) small (less than 1 foot), medium (1 ft. to 20 ft. in length), large (over 20 ft. in length) scale; 4) thickness, followed the classification used for layered rocks as shown in Table 1.

TABLE 1

Classification of bedding and splitting properties of layered rocks
Modified after McKee and Weir (1953)

Bedding	Splitting Property	Thickness
Very thick	Massive	More than 120 cm (4 ft.).
Thick	Blocky	60-120 cm (2 ft.-4 ft.).
Thin	Slabby	6-60 cm (2 in.-2 ft.).
Very thin	Flaggy	1-5 cm (½ in.-2 in.)
Laminated	Shaly (mudstone)	2 mm-1 cm.
	Platy (limestone and sandstone)	2 mm-1 cm.
Thinly laminated	Fissile	Less than 2 mm (paper thin).

In order to achieve uniformity and consistency of recording field notes, in the measurement of the stratigraphic sections, special techniques were devised for field personnel. This design consisted of a rubber stamp for easy recording of field data; the form and kind of data collected are shown in Table 2.

TABLE 2

Rubber stamp used by Arizona district (GW) U.S.G.S.to systematize description of stratigraphic sections

The stamp is imprinted in the notebook for each bed or unit described

Type :
Color : F W
Text : vc - c - m - f - vf - s - c
Rounding : wr - r - sr - sa - a Sort : good fair poor
Cement : hard firm weak Type :
Comp :
Acc : qtz feld mica femag $CaCO_3$ arg
INCL : rare com abund Type :
Bed : fl mas gnrl irr fs vt t tk vtk ( )
X-Bed : TAN sim comp wedg H L Fest : nor plung asy
: 0 - 1″ - 20″ to aeol Fluv Other :
Surface MK :
Base : grad sharp flat irr
Topo : CL ver rnd irr LDG SL reg irr roll COV
Wea : sm rnd blky pit knob Etch
Fossils :
Aquif : good fair poor Recharge : good fair poor
Thickness : Field :

It is pertinent to point out that the stamp technique and type of data collected was designed for the particular geologic environment of the Navajo country. The concept and format of this technique could be used elsewhere but the details of the design would have to be in accordance with the peculiar features of the geologic environment under study.

Explanation

TYPE : Insert «sandstone», «siltstone», «limestone», etc.

COLOR : F — color of fresh fracture

W — color of weathered surface

TEXT (Texture) :

vc — very coarse : 2 mm — 1 mm
c — coarse 1 mm — 0.5 mm
m — medium 0.5 mm — 0.25 mm
ff — fine 0.25 mm — 0.125 mm
vf — very fine 0.125 mm — 0.065 mm
s — silt size 0.065 mm — 0.004 mm
c — clay size less than 0.004 mm

ROUDING : wr — well-rounded
r — rounded
sr — sub-rounded
sa — sub-angular
a — angular

SORT (Sorting) :

CEMENT (degree of cementation) :
hard, firm, weak

TYPE : List cementing minerals, etc.

COMP (Composition) : Show dominant minerals, etc.

ACC (accessory minerals) :
qtz — quartz
feld — feldspar
mica — mica
femag — ferromagnesians
CaCO — calcium carbonate
arg — argillaceous material

INCL (inclusions) :
rare — rare
com — common
abun — abundant

TYPE : Describe or identify

BED (bedding) :
fl — flat
mas — massive
gnrl — gnarly
irr — irregular
fs — fissile
vt — very thin (1/2-2 in)
t — thin (2 in-2 ft)
tk — thick (2-4 ft)
vtk — very thick (4 ft and more)

X-BED (cross-bedding or cross-laminations) :
TAN — tangential
sim — simple
comp — compound
wedg — wedge
0 — 1′ — 20′ to
0 — 1′ — small scale
1′ — 20′ medium scale
20′ over — large scale
H — high-angle
L — low-angle
FEST — festoon
nor — normal
plung — plunging
asy — asymetrical
aeol — aeolian
Fluv — fluviatile
Other — describe

SURFACE MK (surface markings) : Describe

BASE : grad — gradational
sharp — sharp
flat — flat
irr — irregular

Topo (topographic expression):
CL — cliff
ver — vertical
rnd — rounded
irr — irregular
LDG — ledge
SL — slope
reg — regular
irr — irregular
roll — rolling
COV — covered

Wea (weathering characteristics):
sm — smooth
rnd — rounded
blky — blocky
pit — pitted
knob — knobby

Etch (etched characteristics)—cross-laminations, etc.
Fossils : Describe type occurrence, and preservation
Aquif (Aquifer): good, fair, or poor expectation from field observations

Recharge :
Thickness : Field — field units or intervals
True — true value, corrected for dip

2.2. *Development of Correlation Diagrams and Subdivision of Aquifers*

The rocks in the Navajo country have been deformed by gentle folding into anticlines, synclines, monoclines, and gentle dipping homoclines. There are several major faults in parts of the area, but they do not constitute major structural features, and consist mostly of grabens and vertical faults. The rocks in the area generally are well exposed and readily accessible for measurement of stratigraphic sections. Subsurface information was obtained from drill cuttings and drillers' logs of wells. Samples of drill cuttings were collected at 10-foot intervals from all wells constructed during the investigation. These samples were analyzed in the laboratory similarly to the outcrop samples. The information obtained from the field and laboratory were compiled into stratigraphic descriptions of rock units or lithologic logs of rocks encountered by drilled wells.

Definitive evidence of stratal relations were obtained through the mapping program. Field mapping was done on stereophotos at a scale of 2 inches to one mile, at which there was ample detail for showing relationship of the stratigraphic units. This information was compiled on 15 minute quadrangle mosaics. Quadrangle geologic maps were made from these sheets for compilation of a regional geologic map of the Navajo country.

In the development of the correlation charts, a fence-diagram such as the Glen Canyon Group of the Jurassic rocks (fig. 3), was designed to show the relationship of the stratal units. Because the stratigraphic sections provided the most detailed and complete data, they constituted the major controls, supplemented by the well log or lithologic information obtained from the well development program. The combination of these types of control data made it possible to differentiate the various terrestrial sedimentary units and obtain a spatial relationship of the subsurface water-bearing formations.

The Navajo sandstone is an example of the success of these procedures for locating and providing information for well development. Prior to the detailed studies, the Navajo was known to be an excellent aquifer in the region. This formation was assumed to occur throughout the area and many dry holes were drilled in its southeastern part. Studies revealed, however, that the Navajo sandstone does not occur in this section and explained why water had not been encountered in the dry holes. Further attempts to develop water wells in the southeastern part were not made after this stratigraphic information was known and resulted in a saving in funds several times the cost of the studies.

Fence diagrams, similar to figure 3, were constructed for the other rock groups in the region, namely the Tertiary rocks, the Cretaceous rocks, the Upper Jurassic rocks, the Triassic rocks, and the Permian rocks. After the stratal relations were established, specific areas where water would be encountered were indicated on special maps. Upon the completion of the stratigraphic studies, a general stratigraphic section the waterbearing formations for the entire Navajo country, as shown in figure 2 was compiled. Final determinations indicated the occurrence of eight water-bearing formations or aquifers. Not all of these are major aquifers nor do they occur everywhere in the Navajo country. The synthesis of the geologic mapping data, stratigraphic data, and hydrologic data permitted preparation of aquifer maps, of each water-bearing formation in the region.

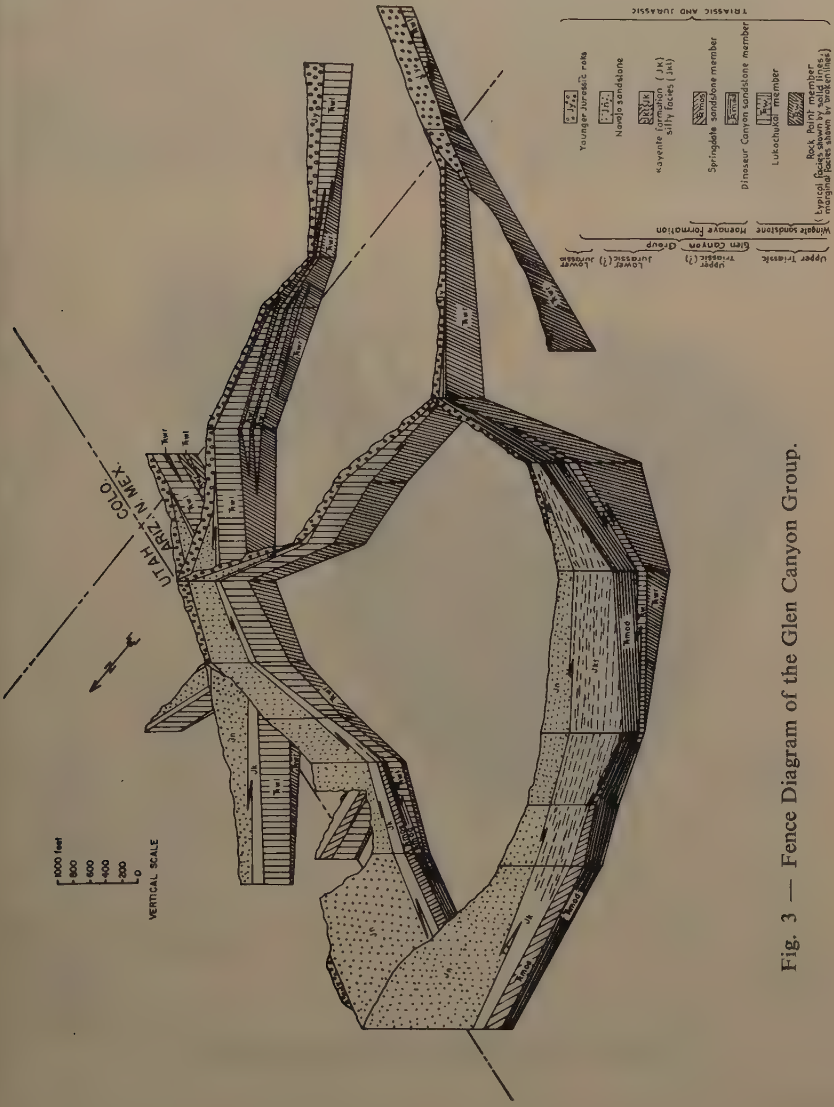

Fig. 3 — Fence Diagram of the Glen Canyon Group.

2.3. *Hydrologic Studies and Data Collection*

A hydrologic inventory accompanied the stratigraphic and geologic studies. The data collection for this program included the location of all drilled and dug wells and occurrence of springs. The locations were made on the stereophotos and compiled on the mosaics, and subsequently transferred to the quadrangle maps. As many of of the water levels in wells were deep, as much as 1500 ft. or more below the surface, special waterlevel measuring devices were developed to obtain accurate measurements. An Ellsworth co-axial steel cable, mounted on a reel for ease of measurement, was found most satisfactory. The measurement device consisted of an electrode sensitive to conductivity of the water and when it contacted the water, a small voltmeter connected to the reel indicated the closure of the electrical circuit. Water samples were collected for chemical analyses in order to obtain information on the quality of the water in each water-bearing unit. More than 2000 chemical analyses were made of water samples, and classified according to stratigraphic occurrence.

A special form was designed for the compilation and recording of the ground-water data for the comprehensive synthesis. A sample of this form is shown in Table 3.

A well development program accompanied the comprehensive investigation which provided an excellent opportunity to obtain information on water yield and chemical quality from the various aquifers. It was not always possible to conduct long period

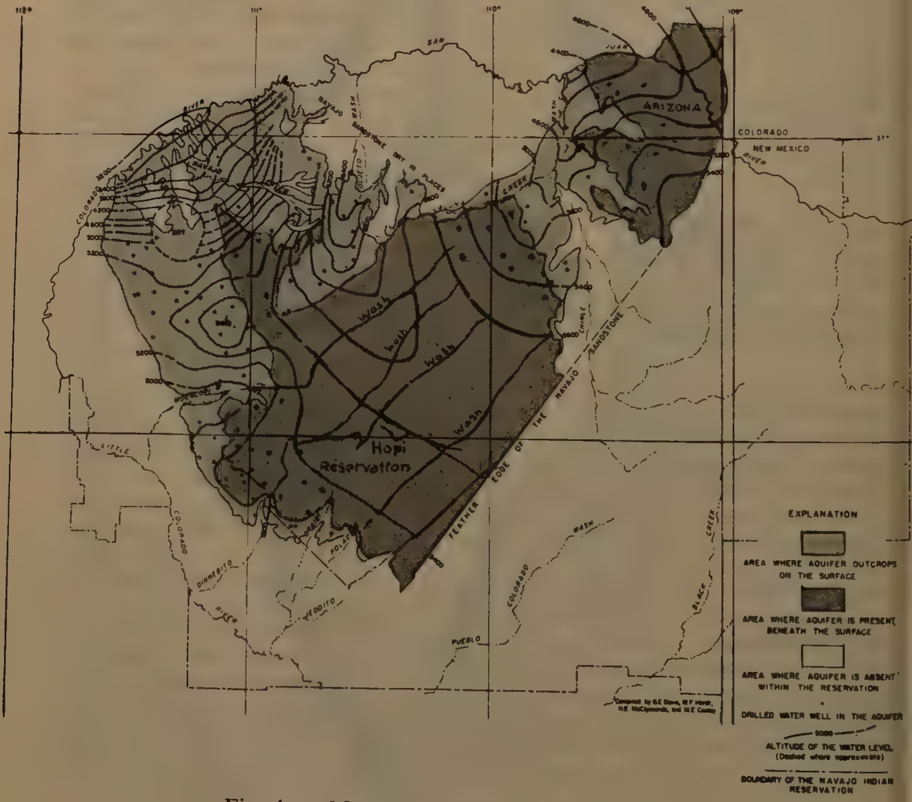
112°
111°
110°
109°
37°
ARIZONA
COLORADO
NEW MEXICO
Hopi
Reservation
Wash
Wash
Wash
Wash
CHINLE
EDGE OF THE NAVAJO SANDSTONE
FEATHER
EXPLANATION
AREA WHERE AQUIFER OUTCROPS ON THE SURFACE
AREA WHERE AQUIFER IS PRESENT BENEATH THE SURFACE
AREA WHERE AQUIFER IS ABSENT WITHIN THE RESERVATION
DRILLED WATER WELL IN THE AQUIFER
ALTITUDE OF THE WATER LEVEL (Dashed where approximate)
BOUNDARY OF THE NAVAJO INDIAN RESERVATION

Fig. 4 — Map of the Navajo sandstone aquifer.

pumping tests as a large number of the wells are in remote areas. Consequently one of the techniques developed to overcome this problem was a short term bailing test to determine specific capacity and aquifer parameters. This technique proved to be successful and inexpensive for obtaining preliminary quantitative data of water-bearing zones and selective water samples. The duration of the bail tests ranged from one hour to less than 10 hours. After the bailing test was completed recovery measurements were obtained for more accurate data to make computations of the cœfficients of permeability and transmissibility. In several places where large quantities of institutional water were needed, long period pumping tests were conducted in order to collect accurate and definitive information. The results of the long period pumping tests were correlated with the data from bailing tests and in general it was concluded that bailing tests provided adequate information for this particular study.

The data obtained from the hydrologic inventory and the well-testing techniques were plotted on aquifer maps to obtain the range and variability of the specific capacity of the several aquifers and their relation to the geologic controls. As shown on figure 4, map of the Navajo sandstone aquifer, the occurrence of the water, direction of movement, and areas where ground water can be developed are easily recognized. The concentration of wells indicates areas where water can be readily developed. Similar aquifer maps were prepared for the Coconino (DeChelly) sandstone (fig. 5), the minor

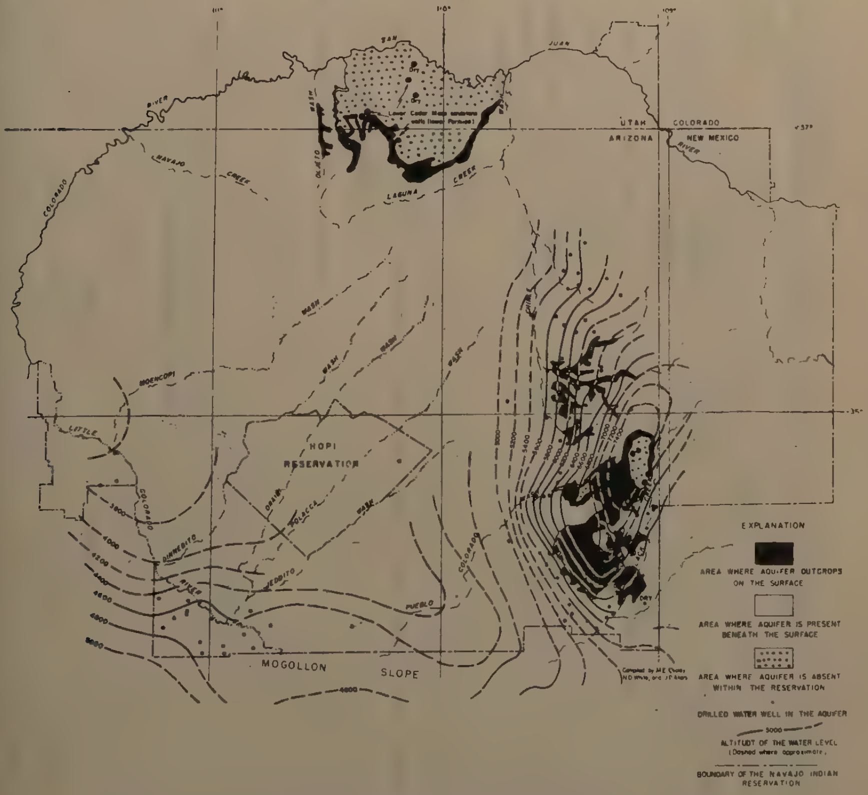
111°
110°
109°
37°
36°
SAN JUAN
RIVER
UTAH
ARIZONA
COLORADO
NEW MEXICO
RIVER
COLORADO
NAVAJO
CREEK
LAGUNA
CREEK
CHINLE
MOENCOPI
WASH
LITTLE
COLORADO
HOPI
RESERVATION
DINNEBITO
JEDDITO
PUEBLO
COLORADO
MOGOLLON
SLOPE
4600
5000
EXPLANATION
AREA WHERE AQUIFER OUTCROPS ON THE SURFACE
AREA WHERE AQUIFER IS PRESENT BENEATH THE SURFACE
AREA WHERE AQUIFER IS ABSENT WITHIN THE RESERVATION
DRILLED WATER WELL IN THE AQUIFER
ALTITUDE OF THE WATER LEVEL (Dashed where approximate)
BOUNDARY OF THE NAVAJO INDIAN RESERVATION

Fig. 5 — Map of the Coconino (DeChelly) sandstone aquifer.

TABLE 3

A form for the compilation of ground water data on the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah (1)

Item No.	Quad No.	Type of Ground-Water Supply or Development	Bureau of Indian Affairs Field No.	Coordinates of Well Location	Location	Date Developed or Completed	Topography	Altitude msl (feet)
4	28	Dr. well	IK-223	4.90-12.75	2-½ mi. WSW of Leche-e Rock	3/54	Edge of mesa	5180
17		Dr. well	IK-217	4.05-10.60	At Kaibito	3/51	Narrow valley	5780

Construction Data

Depth of Well (feet)	Casing or Cribbing		Finish	Improvements
	Diameter Dr. Well (inches) Dug Well (feet)	Depth (feet)		
1417	8-5/8	8	Open hole	None
1240	8-5/8	727	Open hole	Pump

Water-Bearing Strata

Depth to Top (feet)	Thickness (feet)	Type of Material	Stratigraphic Unit
80	1337P	ss	Navajo
90	1140	ss	Navajo

Hydrologic Data

Static Water Level		Yield		Bail or Pump Test		
Depth (feet)	Date of Measurement	Rate (gpm)	Date of Measurement	Rate (gpm)	Drawdown (feet)	Duration of Test (hours)
1360	3/10/54	—	—	6	45	½
558	1/14/53	—	—	30	9	10

Use of Water	Quality		Temp. (°F.)	Remarks
	Chemical Analysis	Sensory Test		
Stock (Unused)	Yes	Good	69	Excessive lift
Public, Stock	Yes	Good	64	Kaibito School

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[1] The separate parts are placed end to end for the heading on data sheets, 3 feet in length and 11 inches in width.

aquifers in the Triassic rocks, the Jurassic rocks, the Cretaceous rocks, Tertiary rocks (fig. 6), and the Alluvium occurring along several of the major drainages in the Navajo country.

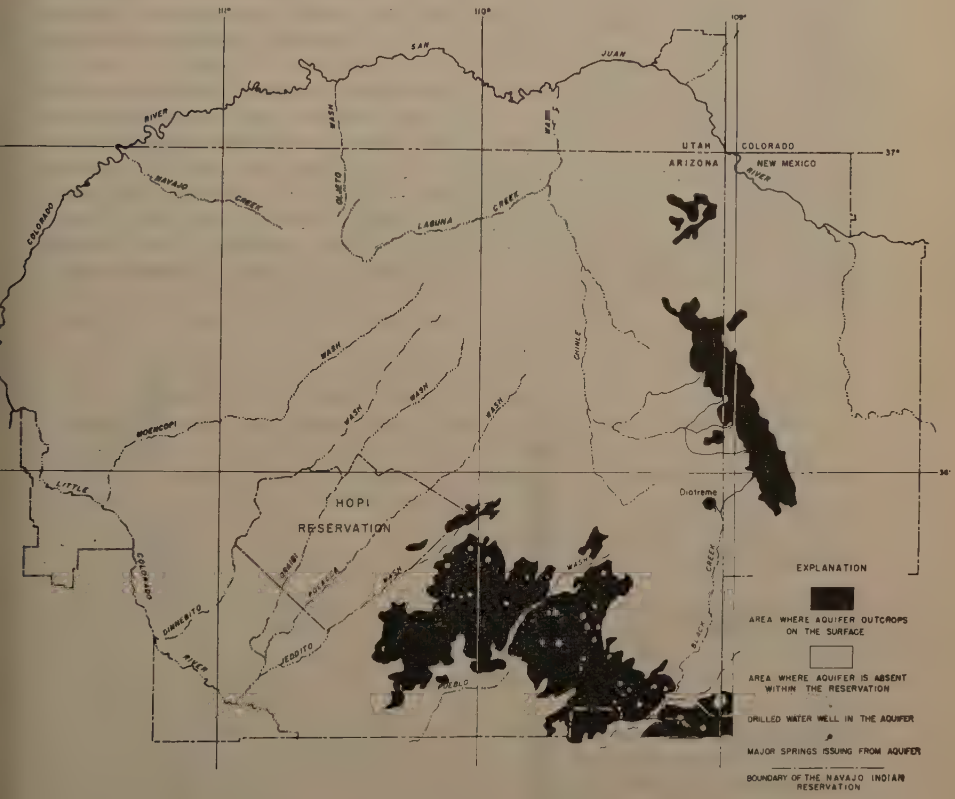

Fig. 6 — Map of the Tertiary rocks aquifer.

Accompanying the aquifer maps, chemical quality maps were made to show the range and variability of salt content in the ground water. Figure 7 shows a range of the chemical content of waters by stratigraphic unit and geographically. The quality of the water is a major problem in the development of adequate water in this region as much of the existing water in storage is unfit for use. Consequently the availability of water for future development is limited. The synthesis of these techniques led to a highly successful well development program in the Navajo country and today well location at specific sites are readily determined in the office without time consuming field inspection.

Another technique to supplement information on the permeability of the sandstone aquifers was the collection of drill-core samples from the outcrop. It was hoped to obtain a relationship of particle size to the permeability of principal aquifers. The cores consisted of 6 to 8 inches in length and 1 inch in diameter, obtained with portable boring equipment. The cores were subjected to standard permeameter tests to determine water yield and transmission cœfficients. The results obtained from these tests were correlated with the data obtained from pump test procedures and flow-net analyses.

Good correlation was not achieved by this technique and it is believed that it is not applicable to a geologic environment such as in the Navajo region. The results did show the relationship of grain size to permeability in that the smaller the grain size the lower the cœfficient of permeability and water yield of the aquifers. Other geologic features such as cementation, compaction, fracturing, shape, sphericity, and packing are significant factors, which cannot be included in laboratory permeability determinations of core samples.

A more fruitful technique for quantitative determinations of sandstone aquifers is a flow-net analysis, which integrates most all geologic factors controlling the behavior of water movement. Although quantitative analyses have not been completed, this technique was used for certain areas where large quantities of water are needed. Subsequent well developments have borne out the value of this technique as larger well yields of water have been obtained than heretofore. In the future, in areas where large quantities of water are needed, this technique may be utilized effectively provided sufficient hydrologic data information are available to construct an accurate water level map.

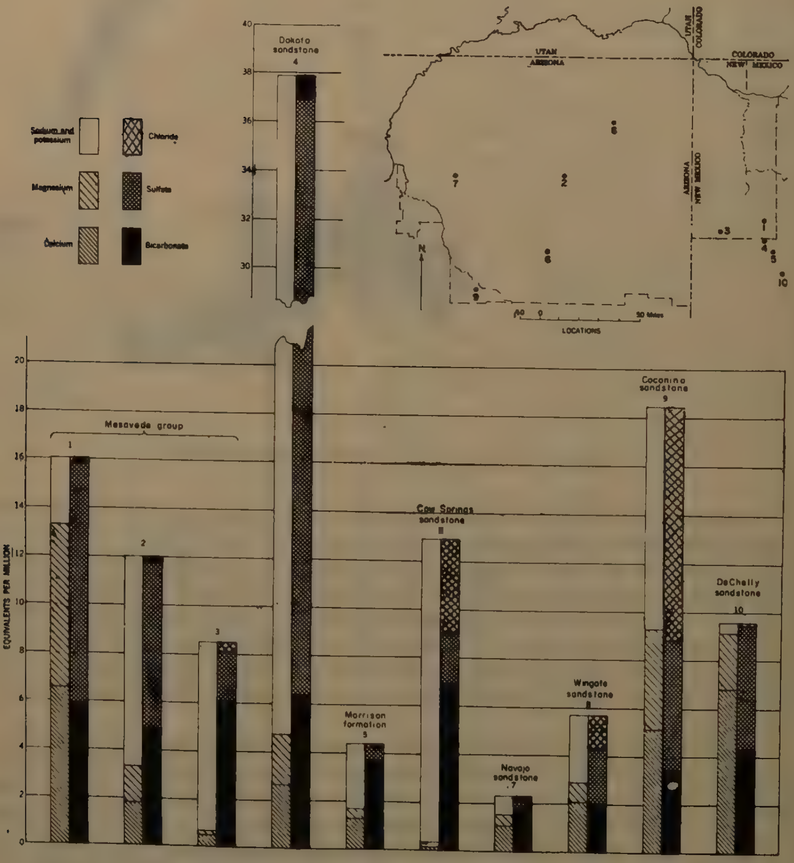

Fig. 7 — Dissolved mineral matter in ground waters in the Navajo country.

3. RESUME OF GEOHYDROLOGIC CONDITIONS

The compilation and synthesis of the data collected from the foregoing techniques were essential to prepare the overall geohydrologic relationships for the Navajo country. The stratigraphic column as shown in figure 2 indicates the superposition of the various geologic formations and their water-bearing zones. This section does not reflect all the detail relationships as shown in the stratigraphic fence diagrams. However, if all the formations occurred at a single site in the Navajo country, they would appear as shown. Further, the stratal relations differ throughout the area; for example, the Shinarump conglomerate is shown as overlying the Moenkopi formation which in turn overlies the Kaibab limestone. Such is the case in the western part of the reservation, but, in the eastern part the Shinarump conglomerate rests directly on the Coconino (DeChelly) sandstone of Permian age. Here, the Shinarump and the Coconino form a common aquifer whereas in the western part they occur as two separate aquifers. Another example of an aquifer, comprising rock units of different age is the Dakota sandstone of Cretaceous age lying directly on the Morrison formation of Upper Jurassic age. These sandstone units form a common aquifer and it is difficult to recognize the separate sandstones from drill cuttings.

Several broad conclusions drawn from the geohydrologic studies are as follows: 1) The total thickness of strata is more than 8000 feet but only about 30 percent are water-bearing reservoirs; 2) the storage capacity of the water-bearing formations is probably not more than 25 percent of the gross volume of the rock; 3) less than one-tenth of the water in storage is feasible for withdrawal by wells; 4) the water-bearing formations are not present everywhere in the Navajo country, which further reduces the availability of water supplies. Only the Coconino (DeChelly) sandstone has the most widespread distribution; and 5) eight principal water-bearing zones or aquifers have been differentiated.

The aquifers in the Navajo country are fine-grained sandstone intercaleted with non-water-bearing layers of siltstone and claystone. The distribution of the aquifers and aquicludes and their complex boundary relationships are of considerable economic importance in water development. In many places the chemical quality of water is an important factor as large amounts of dissolved solids in certain aquifers require development in other water-bearing zones to obtain suitable water. Further, there are only three major aquifers based on water yield, distribution, and chemical content: A resume of the characteristics of these major aquifers is given in the following paragraphs.

1. *Coconino (DeChelly) sandstone of Permian age*—This aquifer underlies nearly all the region and has an average thickness of 600 feet, but thins to the eastward where it is 200 feet. The formation consists of fine-grained, well sorted, sand, highly cross-bedded, deposited by ancient winds. In places it contains large amounts of cemented material. Underlying the Coconino sandstone, the Supai formation consists of alternating beds of siltstone and claystone. In the main, it acts as aquiclude as it retards the downward percolation of water. As shown on the Coconino (DeChelly) sandstone aquifer map (figure 5), wells have been developed along the southwestern and eastern parts of the region. In the central part of the area the aquifer is several thousand feet below the land surface and the quality of water is high in sodium chloride, thus making it untenable for economic exploitation.

2. *Navajo sandstone of Jurassic age*—The Navajo sandstone is fine-grained, well sorted, contains only a small amount of cemented material, and is also an ancient dune deposit. It is wedge shaped formation, about 1500 feet thick at Lees Ferry, and thins eastward and pinches out near the Arizona border. This sandstone is the best waterbearing formation in the western part of the region.

Almost everywhere the Navajo has been penetrated by wells it yields small amounts of water. Ground water in this aquifer, in most areas, occurs under unconfined conditions. However, in the Tuba city area intertonguing units with the Kayerta formation accounts for local artesian water conditions. The yield from the Navajo sandstone ranges widely, from less than 10 to more than 300 gpm. The quality of water in this formation is excellent everywhere encountered by wells. Movement of water in the Navajo sandstone is southeastward toward the Black Mesa Basin and toward the Colorado River in the northwestern part of the reservation.

3. *Mesaverde group of Cretaceous age*—The Mesaverde group comprises several formations of alternating sandstone and grey-black siltstone strata. The basal unit consists of coarse-grained clastic sandstone and commonly yields the largest amounts of water. In the eastern part of the region, nortwestern New Mexico, the basal sandstone is the best water-yielding zone. Here, several wells have produced as much as 200 gpm from the basal member. In general the sandstone units will yield 15 to 50 gpm and well depths range from 200 to 1200 feet. The chemical quality of water from Cretaceous rocks is only fair, except in local places.

In addition to the sandstone aquifers shown in figure 2, groundwater occurs in the shallow alluvium along the main drainage systems such as the Little Colorado River and its tributary drainage system in the central part of the region. The storage capacity of the alluvial material is limited, as it is only a few tens of feet thick and the width is commonly less than one mile. The fine-grained character of the Alluvium is not favorable for any large sustained yield. Production from wells ranges widely from less than 5 to 200 gpm.

The sandstone aquifers in the Navajo, in most places, do not yield more than 300 gpm of water. The character of the rocks does not permit withdrawal of large quantities of water. Where the sandstone strata have been faulted and fractured they provide additional storage space and a greater permeability. Consequently, large quantities of water are produced from wells in those areas where they have been modified by tectonic activity. Such conditions occur near Flagstaff, St. Johns, and Snowflake south of the Navajo country area. Wells in the Flagstaff area yield as much as 700 gpm and near St. Johns a well was observed to yield as much as 1800 gpm.

Flagstaff area—The geologic structural conditions are the controlling factors on the occurrence and availability of ground water at the City of Flagstaff water well field. The post volcanic faulting provided favorable subsurface conditions for accumulations of ground water. The Oak Creek fault (figure 8) trends north-south, near Woody Mountain, southward to Oak Creek. The well field is located on the downthrown side of a normal vertical fault. A transverse fault intersecting the Oak Creek fault are the main zones of fracture. These geologic conditions were the main factors in making the decision for prospecting and exploration of ground water in this area.

Wells were constructed to approximately 1500 feet deep and penetrated the entire thickness ot the Coconino sandstone. Information from the drilling operations shows that supplementary faults occur between each well and clearly indicates the wells are in a fault zone (fig. 8). The water yield and the quantitative aquifer parameters further collaborate these conditions. The completion of the first well resulted in a production of 300 gpm. Three additional wells have been drilled and tests indicate they are capable of producing from 500 to 700 gpm. Preliminary tests of all wells indicate that the field, when fully developed, may produce about 5 million gallons per day. Thus, the the Flagstaff community is assured of a dependable water supply for future growth and expansion.

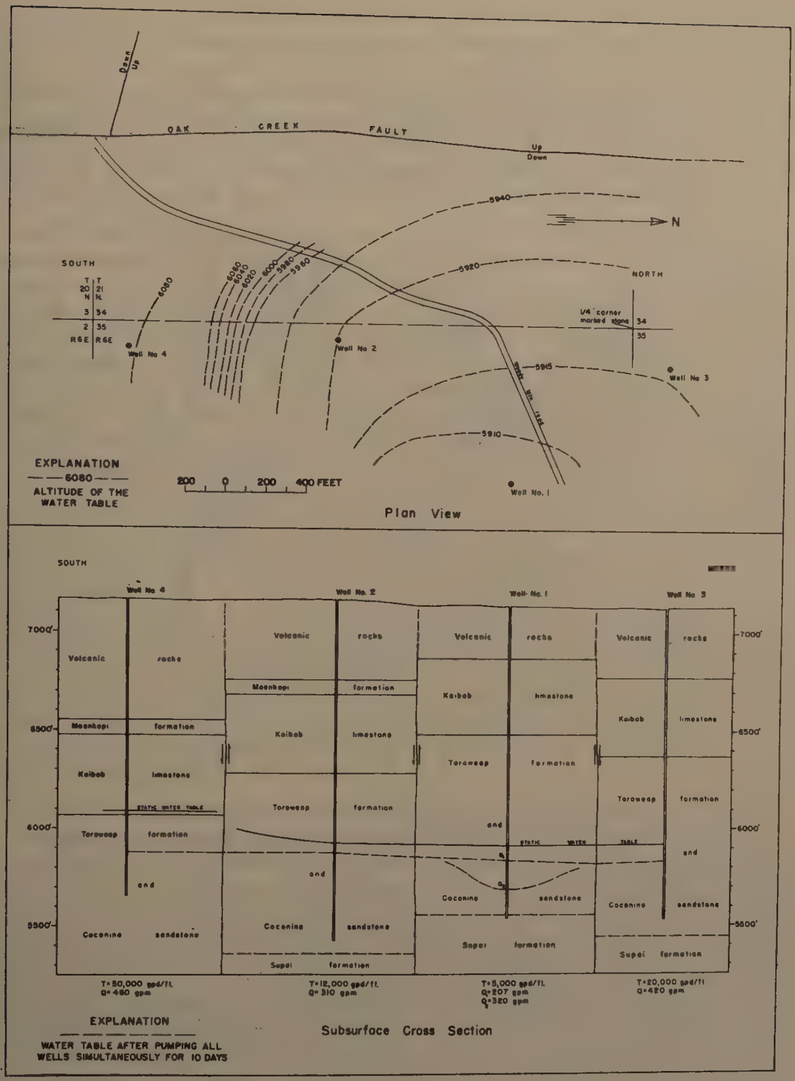

Fig. 8 — Map and subsurface cross section of City of Flagstaff, Arizona water well field.

4. SUBDIVISIONS OF THE NAVAJO COUNTRY AND GROUND-WATER FACTS

In order to determine the feasibility of developing ground water, by geographic area, for domestic, irrigation, industry, and livestock purposes the region was divided into water provinces. Based upon a geohydrologic synthesis, eight principal subdivisions, as shown in Figure 9, were made and the water fact are briefly summarized for each of these areas.

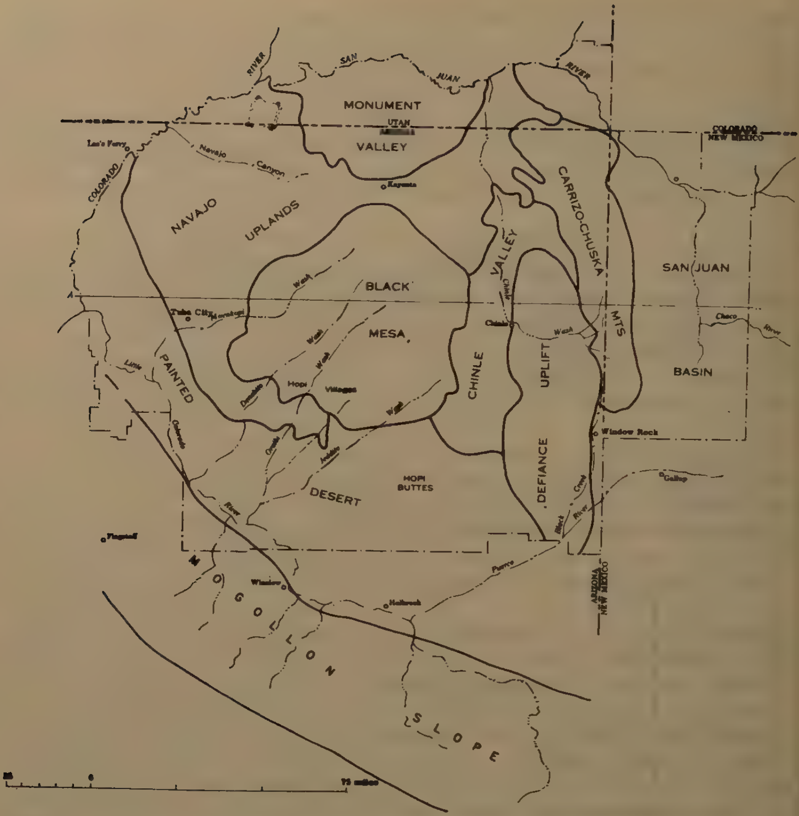

Fig. 9 — Map showing principal subdivisions of the Navajo country.

Mogollon Slope—The subdivision includes the area between Flagstaff and St. Johns; the Mogollon rim and the Little Colorado River. Ground water is obtained mainly from Coconino sandstone aquifer in wells ranging from 200 to 1000 feet deep, however, several wells near Flagstaff are about 1500 feet deep. Water production from the wells ranges from 200 to 3000 gpm. For the most part the aquifer is unconfined and water levels range from a few feet along the Little Colorado River to more than 1200 feet in theFlagstaff area. The chemical quality of ground water between St. Johns and Hunt is only poor to fair, but elsewhere it is excellent.

Painted Desert—The Painted Desert subdivision is a barren bad land country along the southern and western periphery of the Navajo reservation and north of the Little Colorado River. Water is extremely scare in this subdivision. The Triassic and Permian rocks are either dry or contain water high in sodium chloride. Essentially all potable water is obtained from shallow springs issuing from the base of lava flows capping the Hopi buttes, shallow dug wells in the thin alluvium, and drilled wells in the Tertiary rocks. The yield from the Tertiary rocks aquifer is very small (1 to 5 gpm) as the rocks are fine-grained and a limited storage reservoir. One well obtains good water from a borehole in a diatreme. A deep well penetrating the Coconino sandstone encountered water containing more than 10,000 parts per million (ppm) of sodium chloride, attesting to occurrence of unsuitable water.

Navajo Uplands—This extensive terraced plain lies in the northwestern part of the Navajo country where most of the rock outcrops are of Jurassic age. Nearly all the wells in this area obtain excellent water from the Navajo sandstone, the most dependable source of ground water in the entire Navajo country. Although most wells yield small amounts of water, several in the Tuba City area yield as much as 200 (gpm). Depths of wells range from 200 feet in the Tuba City area to more than 1400 feet in the nortwestern part. The water levels range from less than 100 feet to more than 1300 feet and the aquifer is unconfined in most of the area.

Black Mesa—Black Mesa is a partly wooded area, about 85 miles in diameter and ranges in altitude from 5000 in the southern part to 7000 feet in the northern part. The southern part includes the mesas where the Hopi people established their communities. Except for several shallow wells in the alluvium, nearly all the ground water in this area is obtained from Cretaceous sandstone. Springs issue from the base of the Mesaverde group at the boundary of the Mancos shale and constitute an important source of domestic water for the Hopi. Most of the drilled wells obtain water from the sandstone in the Mesaverde at depths from 200 to 600 feet, but several wells obtain water from the Dakota sandstone at depths of 200 to 1000 feet. Water from the alluvium and the Dakota sandstone commonly is marginal in chemical quality for domestic use, whereas water from the Mesaverde group is generally of good quality. Yields of wells in this subdivision range from 5 to 30 (gpm) and water levels occur at comparative shallow depths (200 to 500 feet).

Monument Valley—Monument Valley subdivision lies in the north central part where to a large extent alluvial springs are the main water supply. Little ground water is available to wells even though there are extensive occurrences of Permian rocks. Only two successful wells have been completed to date in the lower part of the Permian sequence. These are 400 and 900 feet deep respectively. Several other holes drilled in this formation were dry. A few dug wells obtained water from the alluvium in the Monument Valley but is many of the washes it is dry. Water from both the alluvium and the Permian rocks is of good quality.

Chinle Valley—The Chinle Valley area includes a broad barren valley formed in Triassic rocks having a scenic array of colors similar to the Painted Desert. It lies between the Chuska Mountains of the east and the Black Mesa on the west. Ground water is available in alluvium along Chinle wash at depths less than 300 feet. Water is obtained from the lower Triassic and the Coconino (DeChelly) sandstone aquifer at depths as great as 2000 feet. The water is under artesian pressure, thus water levels are commonly less than 500 feet. Wells in the alluvium yield from 25 to more than 200 gpm of fair to poor water. The Permian aquifers yield from 50 to more than 100 gpm of moderately good quality water. Near the west side of the valley the chemical content of water from the aquifer is high in sodium chloride and is not suitable for man or beast.

Defiance Uplift—The heavily wooded Defiance Uplift is a broad elongate anticlinal structure, the crest is about 8000 feet above sea level, in the southeastern part. The area receives considerable rainfall and has many natural watering places, therefore, ground water has not been extensively developed. Small amounts, 10 to 20 gpm of good water are available from the Coconino (DeChelly) aquifer at depths ranging from 200 to 500 feet in most of the area; but several holes were dry in this formation. Here, successful wells have been developed by taking advantage of the structural elationships and minor faulting features where fault traps account for the accumuration and storage of ground water capable of yielding sufficient water for domestic land stock purposes.

Chuska-Carrizo Mountains—This subdivision lies along the Arizona-New Mexico boundary in the northeastern part of the region. The area receives about 20 inches of precipitation annually and is heavily wooded. Very few wells have been drilled in this area as adequate water for domestic and stock purposes is obtained from many springs, clear lakes, and several perennial streams. The base flow from nearly all the springs and streams in the Chuska-Carrizo Mountains is discharged from the base of the Tertiary lava and sandstone (Figure 6), which constitute the source and perennial character of streams in this area.

5. CONCLUSIONS

Most of the aquifers in the Navajo country consist of fine-grained, well sorted, moderately-cemented sandstone. They contain large amounts of ground water in storage under non-artesian and artesian conditions. Depths of wells range from ten feet to more than 2000 feet. The exact depth at a particular point is dependent upon the geologic conditions constituting the primary controls on the occurrence and yield of suitable water. Although there are large amounts of water in storage, the yield to wells is not large, owing to the low permeability of the fine-grained sandstone. Calculations indicate there are about 5 billion acre feet in storage in the Navajo Uplands. The amount that can be feasibly withdrawn may be about 50 million acre feet over a long period of time.

Where faulting and fracturing have modified certain formations the permeability has been greatly increased and water yield from wells are several times more than normally expected. In the main, sufficient ground water supplies can be developed for domestic, livestock, and small industrial demands. There are several specific areas where adequate water is available for large industrial demands and limited irrigation projects. On the other hand, there are areas where ground water is beyond practical reach of wells or the chemical quality of water is unfit for any purposes.

The application of particular techniques and well-founded scientific principles has made it possible to unravel the occurrence and character of the ground water system and understand the flow behavior. The collection and synthesis of physical facts permitted definitive conclusions on the availability of water, quantity, and chemical quality for potential development to meet the economic expansion of the region. This synthesis also indicates the limitations of the region, in that large quantities of water are not available for extensive irrigation purposes. Speculation on the future development of water by appplication of reservoir mechanics techniques to modiy the fine-grained aquifers similar to that caused by natural tectonic forces presents challenging possibilities. When adequate forces can be wrought artificially and inexpensively then it will be possible to look forward to the production of large quantities of water from the vast storage reservoir in the fine-grained aquifers in the Navajo country.

6. ACKNOWLEDGMENTS

The author has drawn copiously from numerous reports, prepared by colleagues, for this paper. As the Navajo ground-water investigation entailed the work of about 10 professional geologists and engineers for approximately 10 years, it is difficult to separate the total contribution by each person. The principal colleagues engaged on the comprehensive study were as follows: J. P. Akers, J.T. Callahan, M. E. Cooley, G. E. Davis, W. F. Hardt, J. H. Irwin, Wm. Kam, H. G. Page, C. A. Repenning, and P. R. Stevens. The author expresses his grateful appreciation for their valuable

work and to A. N. Sayre, Chief Ground Water Branch, U. S. Geol. Survey for his stimulating guidance. In addition, John Hem and J. L. Hatchett provided valuable assistance on the quality of water studies and geochemical relations. H. E. Skibitzke developed special techniques to determine aquifer parameters and hydrologic synthesis. Thanks are due George S. Smith for his excellent preparation of numerous illustrations.

The regional ground-water study could not have been made without the financial assistance of the Bureau of Indian Affairs. The highly successful well-development program is attributed to John J. Schwarz (deceased), who provided invaluable hydrologic information and enthusiastic support. The facilities and geologic information of the Museum of Northern Arizona were made available; E. D. McKee, director of the Museum's geologic studies, assisted project personnel in many ways on regional stratigraphy.

SELECTED BIBLIOGRAPHY

Akers, J.P. and Harshbarger, J.W., 1958, Ground Water in Black Mesa basin and adjacent areas: *New Mexico Geol. Soc. Guidebook*, 9th field conf., p. 173-183.

Akers, J.P., Cooley, M.E., and Repenning, C.A., 1958, Moenkopi and Chinle formations of Black Mesa and adjacent ares: *Nex Mexico Geol. Soc. Guidebook*, 9th field conf., p. 88-94.

Akers, J.P., White, N.D., and Harshbarger, J.W., 1959, Woody Mountain Water Well Field-City of Flagstaff, Arizona: U.S. Geol. Survey progress report.

Akers, J.P., McClymonds, N.E., and Harshbarger, J.W., 1961, Geology and ground water of the Red Lake area, Navajo Indian Reservation, Arizona and New Mexico: U.S. Geol. Survey, Water Supply Paper (in press).

Callahan, J.T. and Cushman, R.C., 1955, Geology and ground water supplies of the Fort Wingate Indian School area, McKinley County, New Mexico: U.S. Geol. Survey Circular 360.

Callahan, J.T., Kam, Wm., and Akers, J.P., 1959, The occurrence of ground water in diatremes of the Hopi Buttes area, Arizona: *Northern Ariz. Soc. Sci. & Art. Plateau* v. 32, p. 1-12.

Cooley, M.E., 1958, Physiography of Black Mesa basin, Arizona: *New Mexico Geol. Soc. Guidebook*, 9th field conf,. p. 146-150.

Cooley, M.E., 1958, The Mesa Redondo member of the Chinle formation, Apache and Navajo counties, Arizona: *Northern Ariz. Soc. Sci. & Art, Plateau* v. 31*t* p. 7-15.

Goddard, E.N. (chm.) and others, 1948, Rock-color chart: Natl. Research Council Washington, D.C.

Gregory, H.E., 1916, The Navajo country: U.S. Geol. Survey Water-Supply Paper 380.

Harrell, M.A., and Eckel, E.B., 1939, Ground-water resources of the Holbrook region, Arizona: U.S. Geol. Survey Water-Supply Paper 836-B.

Harshbarger, J.W., and Repenning, C.A., 1954, Water resources of the Chuska Mountains area, Navajo Indian Reservation, Arizona and New Mexico: U.S Geol. Survey Circ. 308.

Harshbarger, J.W., Repenning, C.A., and Callahan, J.T., 1953, The Navajo country, Arizona-Utah-New Mexico, in The physical and economic foundation of natural resources, Part IV, Subsurface facilities of water management and patterns of supply—Type area studies: House of Representatives, Interior and Insular Affairs Committee, p. 105-129.

Harshbarger, J.W., Repenning, C.A., and Irwin, J.H., 1957, Stratigraphy of the uppermost Triassic and the Jurassic rocks of the Navajo country: U.S. Geol. Survey Prof. Paper 291.

McKee, E.D., and Weir, G.W., 1953, Terminology for stratification and cross-stratification in sedimentary rock: *Geol. Soc. America Bull.*, v, 64, p. 381-389.

Pierce, W.H., 1958, Permian sedimentary rocks of the Black Mesa basin area: *New Mexico Geol. Soc. Guidebook*, 9th field conf., p. 82-87.

Repenning, C.A., and Page, H.G., 1956, Late Cretaceous stratigraphy of Black Mesa, Navajo and Hopi Indian Reservations, Arizona: *Am. Assoc. Petroleum Geologists Bull.*, v, 40, no. 2.

Repenning, C.A., Lance, J.F., and Irwin, J.H., 1958, Tertiary stratigraphy of the Navajo country: *New Mexico Geol. Soc. Guidebook*, 9th field conf., p. 123-129.

Wentworth, C.K., 1926, Methods of study of sediments: Univ. of iowa Studies, v. 11, no. 11.

HYDROCHEMISTRY OF THE PARNASSOS-GHIONA AQUIFERS AND PROBLEMS OF SEA-WATER CONTAMINATION IN GREECE

David J. BURDON (1) and ATHANASSIOS DOUNAS (2)

RÉSUMÉ

La composition chimique moyenne des diverses eaux du calcaire dolomitique, du flysch, des alluvions, du conglomérat et du calcaire schisteux de la région de Parnasso-Ghiona a été déterminée par l'analyse de 119 échantillons. Les eaux contaminées par l'eau de mer ont été mises à part et les 16 types, sous-types et eaux moyennes ont été portées sur le diagramme de Durov. De hautes teneurs en nitrates ont été trouvées dans neuf échantillons provenant du voisinage de villages. Les rapports Ca : Mg des eaux des calcaires dolomitiques non contaminées ont été examinées en détail. Mg l'emporte sur Ca dans les eaux des dolomites ou des calcaires magnésiens qui sont venues en contact avec le flysch riche en serpentine. De hautes teneurs en magnésium ont été trouvées dans d'autres dolomites et calcaires, parfois provoquées par le contact avec la serpentine. Cependant, la plupart des eaux des calcaires dolomitiques montrent normalement une teneur faible en Mg et riche en Ca. Une comparaison a été faite entre les rapports Ca : Mg des eaux des couches carbonatées et celles de la nappe du flysch. Aucune corrélation n'a pu être établie entre le rapport Ca : Mg et la porosité des couches.

Basée sur leur teneur en chlorure, on a trouvé que 19 échantillons contaminés par la mer d'eau des calcaires contenaient de 10 à 95% d'eau de mer. En déduisant les montants appropriés d'eau de mer du Golfe de Corinthe, une composition originelle de l'eau souterraine a été déduite; il a été trouvé qu'une eau souterraine d'une telle composition ne peut exister dans le faciès lithologique de Parnassos-Ghiona. Les mélanges d'eau de mer-eau souterraine montrent une augmentation de leur teneur en (Na + K) et SO_4; les causes de cet accroissement n'ont pu être déterminées. Mg décroît quand Ca et HCO_3 augmentent; en partie cela peut être dû à l'échange de base. Quand le pourcentage d'eau de mer augmente, il en est de même de l'excès de l'anion sulfate.

ABSTRACT

The average chemical composition of the different waters from the limestone-dolomite, the flysch, the alluvium, the talus, the conglomerate and the shaley limestone aquifers of the Parnassos-Ghiona Region have been determined by the analysis of 119 samples. Waters contaminated with sea-water have been separated, and the 16 types, sub-types and average waters have been plotted on the Durov diagram. High nitrates have been found in nine samples, collected from village areas.

The Ca:Mg ratios in the uncontaminated limestone-dolomite waters have been examined in some detail. Mg exceeds Ca in waters from dolomites or magnesian limestones which have come in contact with flysch rich in serpentine pebbles. High magnesium is found in other dolomites and limestones, some due to contact with serpentine pebbles. However, most of the limestone-dolomite waters show normal low magnesium and high calcium. A comparison has been made between the Ca:Mg ratios of the waters from the carbonate aquifers and those from the flysch aquifer. No correlation could be established between Ca:Mg ratios and the porosity of the aquifers.

Based on their chlorine content, it was found that the 19 sea-contaminated limestone waters examined contained from 10% to 95% sea-water. By deducting the appropriate amounts of Gulf of Corinth sea-water, an original composition was calculated for the postulated groundwater; it was found that a groundwater of such a composition could not exist in the Parnassos-Ghiona lithological facies. The mixed sea-water/groundwater shows strong increases in its content of (Na + K) and SO_4; the causes of these changes are still unknown. Mg decreases, while Ca and HCO_3 increase; in part, this may be due to base exchange. As the percentage of sea-water in the mixed water increases, so also does the amount of the excess sulphate anion.

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1. Field and laboratory data

The information presented in this paper has been obtained in the course of an investigation into the groundwater resources of the Parnassos-Ghiona Region, undertaken jointly by the United Nations Special Fund and the Institute for Geology and Subsurface Research in order to 'determine, test and demonstrate methods for the successful and efficient development of groundwater resources in limestone terrain'.

1.1. *Field data*

The locations from which the 120 water samples were taken are shown on Figure 1 and are briefly indicated in Table 1. The area investigated covers some 1774 square kilometers, embracing the Parnassos mountain complex on the east

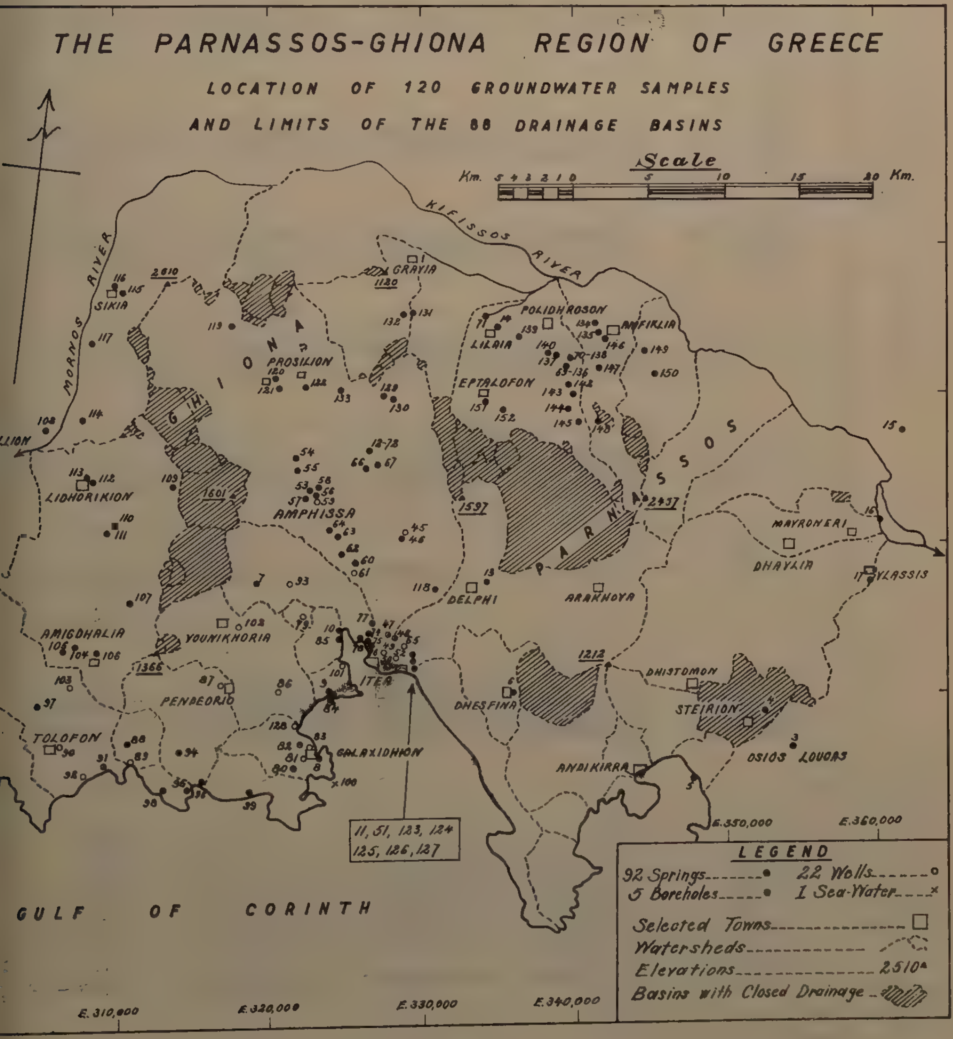


Fig. 1

TABLE 1 a

Location of 120 Samples and Results of Chemical Analyses

No.	Location	Issue	Aquifer	Milligram Equivalents per Litre							P. P. M.
				Ca	Mg	Na + K	HCO_3	SO_4	NO_3	Cl	
3	Osios Loucas	Spring	B	2.00	1.43	2.56	4.15	0.21	0.25	1.38	414
4	Steirion	Gallery	D	1.60	0.60	1.98	2.90	0.16	0.22	0.90	316
5	Andikira	Spring (M)	A	15.00	85.00	351.96	4.48	55.47	0.01	392.00	26270
6	Dhesfina	Spring	A	4.00	0.80	0.02	3.10	0.22	0.85	0.65	366
7	Ay. Evthimia	Spring	A	2.00	0.80	1.05	2.60	0.22	0.04	0.99	281
8	Galaxidhion	Spring	A	5.50	29.80	112.64	5.30	12.61	0.03	130.00	8600
9	Galaxidhion	Spring (M)	A	4.50	21.00	87.91	4.20	9.51	0.01	99.70	6730
10	Myloi	Spring (M)	A	8.80	18.40	91.92	4.40	9.89	0.01	104.83	7020
11	Kirra	Spring	A	8.60	31.00	104.53	4.46	12.53	0.01	127.14	8390
12	Elaion	Spring	A	2.80	1.00	1.13	4.46	0.19	0.03	0.25	386
13	Delphi	Spring	A	2.20	0.40	1.96	4.08	0.20	0.05	0.25	364
14	Lilaia	Spring	A	2.40	0.08	1.27	3.96	0.22	0.05	0.25	351
15	Mavromandalia	Spring	A	3.60	2.00	0.18	5.28	0.20	0.06	0.25	445
16	Mavroneri	Spring	A	2.00	1.00	1.82	4.18	0.19	0.11	0.34	377
17	Vlassis	B. H.	A	1.80	2.07	1.56	3.98	0.64	0.22	0.59	406
45	Proph. Elias	Well	B	2.00	1.50	0.88	3.79	0.06	0.03	0.90	347
46	Proph. Elias	Well	B	1.55	1.04	0.75	2.52	0.11	0.11	0.70	252
47	Itea	B. H.	C	1.59	3.43	14.12	4.16	2.39	0.03	12.50	1219
48	Itea	B. H.	C	1.20	4.09	8.55	4.64	1.20	0.03	5.60	816
49	Itea	Well	C	2.29	6.19	6.94	4.44	3.00	0.03	7.50	965

No.	Location	Issue	Aquifer	Milligram Equivalents per Litre							P. P. M.
				Ca	Mg	Na + K	HCO_3	SO_3	NO_4	Cl	
50	Itea	Well	C	1.49	5.95	6.18	5.84	0.95	0.08	5.00	831
51	Kirra	Spring	A	10.78	25.16	133.13	4.48	23.96	0.21	138.00	9960
52	Itea	Well	C	5.18	7.89	42.41	7.80	9.19	0.03	35.50	3390
53	Amphissa	Spring	B	1.59	0.98	0.33	2.20	0.36	0.05	0.35	224
54	Amphissa	Spring	B	2.19	2.19	0.38	3.78	0.13	0.03	0.20	324
55	Amphissa	Spring	B	1.89	NIL	0.21	1.82	0.12	NIL	0.20	166
56	Amphissa	Spring	B	3.09	2.78	1.52	3.96	0.72	0.68	1.04	499
57	Amphissa	Spring	B	2.09	3.59	0.35	5.24	0.48	NIL	0.60	458
58	Amphissa	Spring	A	1.48	2.93	0.29	3.30	0.30	0.02	0.25	299
59	Amphissa	Well	B	10.98	1.96	4.09	5.88	3.00	3.19	4.30	1245
60	Sernikaki	Spring	B	5.19	2.99	1.78	4.12	2.88	1.36	3.10	767
61	Sernikaki	Well	B	6.58	3.79	1.45	4.12	0.40	1.14	3.80	785
62	Ay. Konstandin.	Spring	B	1.69	2.89	0.36	3.02	0.12	0.04	0.56	290
63	Ay. Konstandin.	Spring	A	1.49	2.89	0.44	0.24	0.24	0.08	0.30	321
64	Ay. Yeoryioe	Spring	A	2.19	0.99	0.28	2.51	0.30	0.14	0.35	253
65	Itea	Well	C	1.95	18.31	64.05	6.93	11.05	0.16	63.80	3690
66	Elaion	Spring	D	1.59	3.09	0.36	3.92	0.48	0.05	0.60	375
67	Elaion	Spring	A	2.69	1.60	0.55	3.16	0.30	0.34	0.05	329
69	Ano Polidhros	Spring	A	1.10	2.00	0.09	3.13	0.24	NIL	0.20	252
70	Ano Polidhros	Spring	A	0.80	3.49	0.09	3.84	0.36	NIL	0.25	321

A = Limestone-Dolomite Aquifer
B = Flysch Aquifer
C = Alluvium Aquifer
D = Talus Aquifer
E = Conglomerate Aquifer
F = Shaley Limestone Aquifer

TABLE 1. b

Location of 120 Samples and Results of Chemical Analyses

No.	Location	Issue	Aquifer	Milligram Equivalents per Litre							P. P. M.
				Ca	Mg	Na + K	HCO_3	SO_4	NO_3	Cl	
71	Lilaia	Spring	A	1.76	0.04	0.15	1.76	0.06	0.08	0.25	164
72	Elaion	Spring	A	1.49	1.90	0.18	3.40	NIL	0.03	0.22	273
74	Itea	Spring (M)	A	13.89	21.99	122.60	5.24	20.66	0.10	134.00	9490
75	Itea	Spring (M)	A	9.68	17.99	102.03	4.42	17.85	0.13	108.00	7760
76	Itea	Spring (M)	A	12.87	19.59	111.82	5.40	21.02	0.08	118.60	8670
77	Itea	Spring	E	2.59	0.40	0.78	2.67	0.60	0.06	0.70	295
78	Itea	Spring (M)	A	43.11	29.18	166.71	5.28	60.22	0.14	176.00	14590
79	Tritaia	Well	C	3.85	0.75	1.09	3.49	0.86	0.10	0.90	405
80	Galaxidhion	Gallery	B	6.38	3.85	3.75	5.44	5.06	0.01	3.79	972
81	Galaxidhion	Well	C	2.69	1.79	6.10	3.87	3.69	0.06	3.38	746
82	Galaxidhion	B. H.	C	5.90	5.69	30.74	4.01	8.50	0.17	30.20	2630
83	Galaxidhion	Well	C	4.39	0.90	3.50	1.97	1.80	0.93	4.00	719
84	Galaxidhion	Spring (M)	A	23.95	103.53	581.80	3.14	113.62	0.23	582.00	42560
85	Myloi	Spring (M)	A	7.18	14.39	57.82	4.16	12.93	0.11	63.00	4780
86	Galaxidhion	Well	D	4.59	0.92	1.84	5.37	0.86	0.04	0.85	548
87	Pendeoria	Well	B	5.09	2.25	0.76	6.86	0.99	0.13	0.45	637
88	Panormon	Spring	A	2.39	0.76	0.55	2.64	0.65	0.10	0.70	294
89	Panormon	Well	C	3.09	2.50	1.80	4.31	0.08	0.09	1.60	463
90	Tolofon	Well	B	5.25	0.54	0.80	3.49	1.00	1.74	1.00	535
91	Eratini	BH (art)	C	2.23	0.56	3.45	4.78	0.95	0.01	0.76	492

No.	Location	Issue	Aquifer	Milligram Equivalents per Litre							P. P. M.
				Ca	Mg	Na + K	HCO_3	SO_4	NO_4	Cl	
92	Eratini	Well	C	4.67	2.02	0.80	5.26	2.50	NIL	0.35	590
93	Ay. Evthimia	Well	C	7.18	1.61	0.98	7.48	1.23	0.66	0.75	775
94	Ay. Pandes	Spring	B	3.79	0.36	0.57	2.86	0.64	0.21	0.60	335
95	Ayioi Pandes	Spring (M)	A	12.07	41.58	194.40	4.29	47.92	0.07	207.00	11260
96	Ayioi Pandes	Spring (M)	E	7.18	14.77	69.91	3.12	19.11	0.04	74.30	5700
97	Tolofon	Spring	A	1.40	0.20	0.39	1.48	0.15	0.01	0.30	148
98	Eratini	Spring (M)	A	12.30	49.97	234.00	3.66	16.64	0.33	257.50	16510
99	Galaxidhion	Spring (M)	E	13.97	60.33	319.20	3.64	24.96	0.36	327.50	21530
100	Gulf of Cor.	Sea-Water	—	23.95	117.94	552.75	3.13	45.70	0.38	618.00	39140
101	Itea	Well	C	9.98	8.79	38.15	3.80	4.16	0.06	44.48	3208
102	Vounikhora	Well	A	4.99	0.20	1.26	5.23	0.12	0.11	0.30	476
103	Amigdhalia	Well	B	2.60	0.40	0.60	3.00	0.12	0.06	0.35	276
104	Amigdhalia	Spring	A	2.60	NIL	0.54	2.46	0.06	0.21	0.22	239
105	Amigdhalia	Spring	B	2.19	0.20	0.19	2.26	0.08	0.09	0.25	205
106	Amigdhalia	Spring	A	5.19	0.20	0.23	5.10	0.12	0.03	0.35	443
107	Melandhrinon	Spring	B	3.59	0.40	0.23	3.61	0.11	0.23	0.25	331
108	Kallion	Spring	A	2.59	NIL	0.13	2.46	0.09	NIL	0.15	215
109	Karoutai	Spring	B	1.39	1.00	0.15	2.10	0.12	0.02	0.20	186
110	Skaloula	Spring	D	1.79	1.40	0.65	1.70	0.99	0.26	0.50	254
111	Skaloula	Spring	D	4.79	0.60	0.38	5.00	0.24	0.09	0.40	449

A = Limestone-Dolomite Aquifer
B = Flysch Aquifer
C = Alluvium Aquifer
D = Talus Aquifer
E = Conglomerate Aquifer
F = Shaley Limestone Aquifer

TABLE 1, c

Location de 120 Samples and Results of Chemical Analyses

No.	Location	Issue	Aquifer	Milligram Equivalents per Litre							P. P. M.
				Ca	Mg	Na + K	HCO_3	SO_4	NO_3	Cl	
112	Lidorikion	Spring	E	1.79	0.20	0.15	1.82	0.08	0.37	0.18	187
113	Lidorikion	Spring	D	4.39	NIL	0.23	3.47	0.20	0.21	0.27	338
114	Lidorikion	Spring	B	2.79	0.80	0.35	2.73	0.31	0.08	0.30	271
115	Sikia	Spring	B	1.79	0.70	0.31	2.25	0.35	NIL	0.25	215
116	Sikia	Spring	D	2.19	NIL	0.10	1.77	0.09	0.28	0.15	182
117	Kevkadhiti	Spring	B	1.36	0.79	0.47	2.02	0.17	0.06	0.35	196
118	Khrison	Spring	D	3.19	0.49	2.04	2.75	0.33	0.90	1.95	433
119	Prosilion	Spring	A	3.19	0.10	0.05	3.24	NIL	0.01	0.10	268
120	Prosilion	Spring	D	3.69	NIL	0.16	3.67	Tr.	0.06	0.20	313
121	Prosilion	Spring	D	4.30	0.20	0.24	4.34	NIL	0.15	0.25	369
122	Prosilion	Spring	E	3.77	0.40	0.18	3.52	Tr.	0.23	0.25	323
123	Kirra	Spring	A	10.77	29.98	156.00	4.16	18.72	NIL	156.50	10930
124	Kirra	Spring	A	9.98	20.79	109.60	4.71	14.00	NIL	106.00	7790
125	Kirra	Spring	A	13.57	30.38	173.30	4.12	22.78	NIL	167.00	11950
126	Kirra	Spring	A	11.57	30.38	175.70	4.24	16.38	NIL	161.00	11450
127	Kirra	Spring	A	12.37	35.58	180.00	4.05	21.20	NIL	173.00	11270
128	Galaxidhion	Well	E	8.78	5.80	36.30	3.57	5.39	0.01	35.50	2824
129	Kalobates	Spring	B	1.78	1.00	0.16	2.18	0.60	0.01	0.15	220
130	Kalobates	Spring	B	2.89	1.80	0.97	3.73	1.40	0.20	0.40	426
131	Varianni	Spring	A	3.39	0.10	0.19	3.60	Tr.	Tr.	0.10	298

No.	Location	Issue	Aquifer	Milligram Equivalents per Litre							P.P.M.
				Ca	Mg	Na+K	HCO_3	SO_4	NO_3	Cl	
132	Varianni	Spring	A	2.19	0.30	0.09	2.55	NIL	NIL	0.15	206
133	Prosilion	Spring	D	2.19	0.40	0.22	2.36	0.10	0.03	0.20	255
134	Amfiklia	Spring	B	3.59	2.69	0.13	6.12	NIL	0.03	0.25	491
135	Amfiklia	Spring	A	4.89	0.50	0.15	5.22	NIL	NIL	0.20	433
136	Ano-Polidhros	Spring	A	1.97	2.29	0.09	3.70	0.50	Tr.	0.15	325
137	Ano-Polidhros	Spring	D	2.56	2.00	0.10	4.48	0.20	Tr.	0.05	364
138	Ano-Polidhros	Spring	A	2.56	2.00	0.08	4.20	0.20	Tr.	0.20	351
139	Polidhroson	Spring	A	2.29	0.50	0.07	2.46	0.20	0.01	0.15	219
140	Polidhroson	Spring	D	2.39	2.50	0.09	4.30	0.50	0.01	0.15	373
142	Polidhroson	Spring	A	0.20	NIL	4.28	1.65	0.60	0.04	1.20	303
143	Polidhroson	Spring	A	1.49	1.89	0.08	3.28	NIL	NIL	0.05	253
144	Polidhroson	Spring	B	1.79	2.00	0.08	3.76	NIL	Tr.	0.05	304
145	Polidhroson	Spring	C	3.79	2.59	0.09	6.02	0.20	0.02	0.20	499
146	Amfiklia	Spring	B	4.19	1.19	0.14	5.14	0.20	0.01	0.20	433
147	Amfiklia	Spring	D	1.60	3.60	0.16	5.08	0.15	NIL	0.15	402
148	Amfiklia	Spring	A	1.69	2.10	0.07	3.06	0.60	Tr.	0.08	291
149	Amfiklia	Spring	B	3.59	2.49	0.15	5.63	0.30	0.11	0.20	473
150	Amfiklia	Spring	F	2.29	0.20	0.11	2.38	NIL	NIL	0.20	203
151	Eptalofon	Spring	A	2.29	0.20	0.08	3.38	NIL	Tr.	0.15	274
152	Eptalofon	Spring	A	2.19	1.40	0.08	3.44	NIL	NIL	0.15	278

A = Limestone-Dolomite Aquifer
B = Flysch Aquifer
C = Alluvium Aquifer
D = Talus Aquifer
E = Conglomerate Aquifer
F = Shaley Limestone Aquifer

and the Ghiona complex on the west, and lies on the north coast of the Gulf of Corinth. Figure 1 shows the 88 drainage basins into which the area has been subdivided, as well as its boundaries at the Mornos River on the north and north-west and the Kifissos River on the north and north-east. The drainage network and the different aquifers and aquicludes are not shown on Figure 1; further information on the hydrogeology will be found in another paper (Burdon and Papakis) to be presented to this meeting.

Table 2 summarises the different aquifers from which the samples have originated, and also the source, such as spring, well or borehole, through which they were discharged from the aquifer. The predominance of springs (92 samples) is very marked, while limestone-dolomite and flysch are seen to be the more important aquifers. Of the 52 limestone waters, 50 come from springs, one (No. 17) from a borehole and one (No. 102) from a well. On the other hand, the alluvium aquifers are tapped almost exclusively by wells and boreholes, only one alluvium water (No. 145) issuing as a spring from a pocket of perched alluvium, lying at an elevation of some 1,330 metres.

TABLE 2

Distribution of 120 water analyses between the different aquifers and water discharge points in the Parnassos-Ghiona Region.

Aquifer	Number of samples	Method of discharge	Number of samples
Limestone-Dolomite	52	Spring, + 100 m^3/hr	19
Flysch	26	Spring, 10-100 m^3/hr	20
Alluvium	16	Spring, – 10 m^3/hr	53
Talus-Coluvium	18	Wells	22
Conglomerate	6	Boreholes	5
Shaley Limestone	1	Sea Water	1
Sea Water	1		
Total	120		120

As may be seen from Figure 1, many of the samples have been obtained at, or close to, the coast. Clear evidence of admixture of sea-water is found in 19 out of the 33 limestone-dolomite waters, in 6 out of the 16 alluvium waters and in 3 out of the 6 conglomerate waters; this problem is discussed in some detail in Section 4 of this study. From Figure 1 it will also be noted that samples are sparse in the extreme north and the south-east of the region under study; these areas have been sampled, but the results of the analyses had not come to hand in time for inclusion in this study.

1.2. *Chemical analyses data*

The results of the 120 chemical analyses are given in as brief a form as possible in Table 1. The analyses have been carried out in the laboratory of the Institute for

Geology and Subsurface Research by Miss A. Papastamataki. For samples up to No. 44, K and Na were determined by difference; thereafter, K and Na were determined on the flame photometer of the Institute of Soils, Fertilizers and Climate, Ministry of Agriculture, thanks to the cooperation of Dr. D. Catacousinos.

In themselves, the analyses call for no comment. It will be noted that No. 100 was a sample of sea-water taken off Ghalaxeidon. It seemed better to get an analysis of the water in the Gulf of Corinth rather than use some standard such as that of Dittmar (1884). The analysis indicated a water some 10% more concentrated than Dittmar's standard sea-water but agrees with Twenhofel (1950, p. 508) for the Mediterranean. The figures are not unexpected for the Gulf of Corinth, but it would have been preferable to have taken more sea-water samples and averaged the results.

Chlorine content has been used as the basis for determining the percentage of sea-water present in mixed waters—see Section 4. It would have been more satisfactory to have used bromine also to determine the exact percentage, for bromine is almost never found in groundwater and is always present in standard amounts in sea-water. Unfortunately, consistent and useable determinations of bromine have not yet been achieved, though work is continuing to establish a satisfactory routine.

2. THE WATERS OF THE SIX AQUIFERS

On lithological grounds, the different geological series present in the Parnassos-Ghiona Region (see the 1:50,000 sheets of the Geological Map of Greece for Amphissa, Parnassos and Parnassos South) can be classified into six lithological categories, as listed in Table 2 of this study. Their transmissibility and storage coefficients vary greatly, and in fact, the flysch generally, and the shaley limestone in its restricted areas, are more aquicludes than aquifers. Nevertheless, specialized facies, or local influences such as weathering or tectonics, impart a limited permeability even to the flysch. However, in this study, attention is concentrated on the chemistry of their waters and the chemical interaction between the aquifer rocks and their waters.

Some snow samples have been collected to get an idea of the initial chemical composition of the precipitation. Until the results come to hand, it has been assumed that precipitation is of the normal, marine-origin type, such as those rains with from 2.3 to 12.6 ppm of chlorine reported by Gorham (1955) from soot-free rains in the Lake District of England. Thus the uncontaminated limestone waters show some 9.4 ppm of Cl (0.265 meq.), and all of this could have originated from the precipitation, when concentration due to evaporation is taken into account.

Table 3 lists averages for 16 different waters, based primarily on the type of aquifer in which they occur. The classification of Table 3 has been used as the basis of Fig. 2, which displays the main chemical characteristics of these waters on the Durov diagram. Waters from the limestone-dolomite and conglomerate aquifers with definite admixtures of sea-water, as well as alluvium waters showing marine influences, have been separated from the uncontaminated waters of these aquifers. For the flysch and talus waters, those with high magnesium content have been distinguished from the more normal low-magnesium waters.

2.1. *Waters from Limestone-Dolomite aquifers*

These are the most common aquifers of the Parnassos-Ghiona Region, and are represented by 52 samples. Of these, 19 are clearly contaminated with varying percentages of sea-water and are considered in detail in Section 4. The remaining 33 samples average 316 ppm total soluble salts, and have an ionic composition as follows:

TABLE 3

Average Chemical Composition of 16 types and sub-types of groundwaters from the six different aquifers of the Parnassos-Ghiona Region. Based on the 120 samples listed in Table 1

No.	Aquifer With Subdivisions based on Ionic Content	Ionic Content, in Milligram Equivalents per Litre							P.P.M.
		Ca	Mg	Na + K	HCO_4	SO_4	Cl	NO_3	
33	*Limestone-Dolomite*	2.428	1.186	0.463	0.200	0.265	0.265	p.008	316
19	Ditto, with sea-water	12.970	34.930	170.930	4.430	27.780	178.350	0.076	12488
14	*Flysch*, calcium carbonate	2.920	1.103	0.481	3.750	0.160	0.060	0.630	345
7	*Flysch*, magnesium carbonate	1.900	2.090	0.770	3.750	0.160	0.060	0.630	345
5	*Flysch*, no dominant anion	6.676	2.626	2.374	4.610	3.188	3.198	1.487	861
26	Average Flysch	3.832	1.940	1.208	3.969	1.243	1.223	0.753	439
6	*Alluvium*, calcium carbonate	4.130	1.670	1.480	5.220	0.970	0.760	0.146	538
4	*Alluvium*, mixed anions	2.440	3.180	6.080	4.080	1.910	4.495	0.275	777
6	*Alluvium*, marine influence	4.480	8.380	32.730	5.190	6.380	32.330	0.079	2517
16	Average Alluvium	3.683	4.410	13.430	4.830	3.087	12.528	0.167	1277
15	*Talus*, calcium carbonate	2.990	0.710	0.571	3.300	0.288	0.386	0.147	324
3	*Talus*, high magnesium	1.860	3.062	0.203	4.430	0.378	0.300	0.019	384
18	Average Talus	2.790	1.128	0.507	3.505	0.304	0.371	0.125	335
3	*Conglomerate*, calcium carbonate	2.710	0.333	0.370	2.670	0.227	0.377	0.219	268
3	Ditto, with sea-water	9.980	26.970	141.810	3.430	16.480	145.770	0.135	10018
1	*Shaley Limestone*	2.290	0.200	0.107	2.380	Nil	0.200	Nil	203
1	Gulf of Corinth, Sea Water	23.950	117.94	552.75	3.13	45.70	618.00	0.38	39144

Cations		*Anions*	
Ca	2.428	$CO_3 + HCO_3$	3.464
Mg	1.186	SO_4	0.200
		Cl	0.265
Na + K	0.463	NO_3	0.008
	4.077, all in meq. units		3.937

These are typical calcium bicarbonate waters, to be expected from well-flushed limestone-dolomite aquifers. Their uniformity over the region makes them a very suitable chemical base from which to study effects of intermingling with sea-water; almost all the coastal springs issue from limestones. However, their calcium: magnesium ratio is variable, and has been treated separately in Section 3.

The purest limestone water analysed contained 148 ppm of total soluble salts, of which 113 ppm are attributable to calcium bicarbonate; it (No. 97) came from a spring in limestone to the north of Tolofon. The most mineralised limestone water came from the well at Vounikhora (No. 102), and contained 476 ppm of total soluble salts; 404 ppm are attributable to calcium bicarbonate.

2.2. *Waters from the flysch aquifers*

While the basal flysch is fine-grained to compact red and grey clay, the middle and upper flysch is coarser, sometimes with pebble beds, and rarely with limestone lenses. In places, the harder sandstone beds are jointed, and are then aquifers. The altered, superficial flysch is an aquifer of low capacity. In all cases, yields from the flysch aquifers are small; but flysch springs are numerous and provide water for many of the villages of the region.

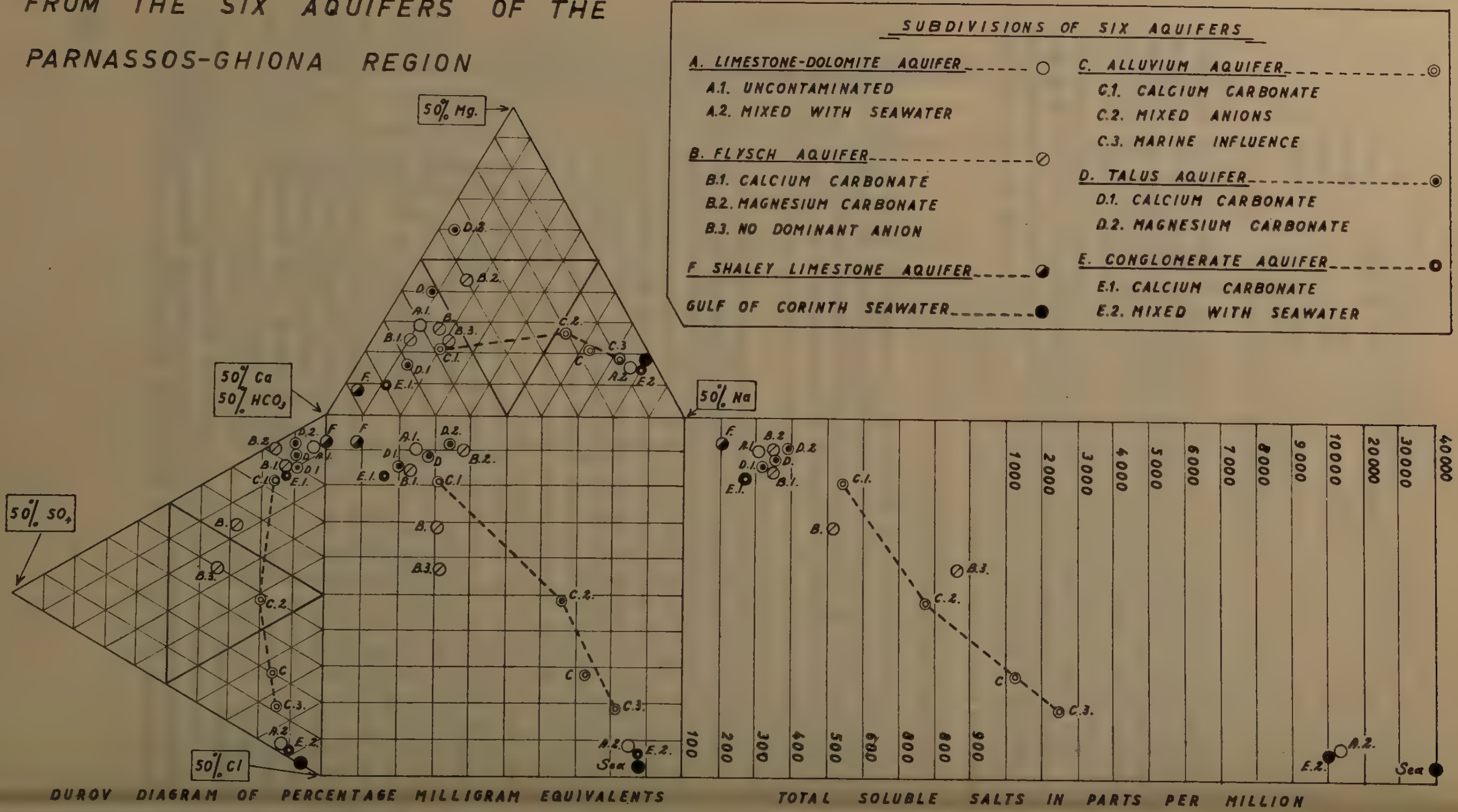
Of the 26 samples of flysch water, 21 are carbonate waters in 14 of which calcium is the dominant cation, while in the remaining 7, magnesium is present in appreciable quantities. The average chemical composition of these two sub-types has been calculated in Table 3 and plotted on Fig. 2. The 14 calcium-carbonate waters have 342 ppm total soluble salts, and may be considered as one of the typical flysch waters.

It must be recalled however, that pebbles of serpentine and other magnesium-rich ultrabasic rocks are common in the coarser facies of the flysch, and may also contribute to the finer constituents of the flysch. Hence, the magnesium-rich carbonate waters are likewise primary flysch waters. They have 345 ppm total soluble salts, and their distribution is of interest. Nos. 3, 45 and 46 come from small spring-wells in conglomeritic flysch at the Osios Loucas and the Prophitis Elias monasteries. Nos. 54, 57 and 62 come from small springs and a well in, or near, Amphissa. This is an area where magnesium-rich waters are also found in the limestone aquifers (3-1 and 3-2). Likewise, the last of these waters, No. 144, comes from a flysch spring south of Polydroson, associated with springs from the overthrust Triassic dolomite of the Eastern Zone.

The Ca: Mg ratios for these seven samples have been plotted on Fig. 3, so that the may be compared with the limestone waters of high Mg content. It will be seen that they all lie close to the 1:1 ratio of Ca: Mg, which in a region of only carbonate rocks would indicate water from a pure dolomite. Since the presence of serpentine is certain, the waters are from limestone-dolomite flysch aquifers, enriched with Mg from serpentines.

Five samples of flysch water contain no dominant anion, and their average chemical composition shows 861 ppm of total soluble salts. They are no longer primary waters, for their initial chemical composition has been altered. In four cases (Nos. 59,

AVERAGE CHEMICAL COMPOSITION OF 16 TYPES AND SUB-TYPES OF GROUNDWATER FROM THE SIX AQUIFERS OF THE PARNASSOS-GHIONA REGION



60 and 61 in Amphissa, and No. 90 in Tolofon) they have been contaminated with organic wastes, and show high NO_3 content. In Fig. 2, the NO_3 has been combined with the SO_4 for plotting, and it is seen that the average of this sub-type of water is the only one from the region with anything approaching 25% of ($SO_4 + NO_3$). In one sample indeed, No. 80, to the west of Ghalaxeidon, which has 972 ppm of total soluble salts, SO_4 accounts for 243 ppm. This spring-gallery in the flysch had almost no flow in summer, and was much frequented by hornets. Many of the flysch springs are said to have medicinal properties; one would expect this reputation to be based on high sulphate content, but No. 80 is the only one which shows a marked content of SO_4. In the alluvium of Ghalaxeidon, however, No. 81, from a gallery-well at the foot of the hills, also shows high SO_4; this confirms the results of No. 80, and suggests that in this area there is a source of sulphur.

2.3. *Waters from the alluvium aquifers*

The 16 samples of water from alluvium aquifers show interesting increases in their content of total soluble salts and the three sub-types have been joined on Fig. 2, to emphasize this type of metasomatic change (Burdon and Mazloum, 1958). Of the 16 samples, six are calcium carbonate waters, but with 538 ppm of total soluble salts; four have no dominant anion, but 777 ppm of total soluble salts; while the remaining six are clearly influenced by encroachment of sea-water and show 2,517 ppm of total soluble salts.

The alluvium waters considered here are found around Itea, Ghalaxeidon and Eratini. Much of the alluvium water must originate by direct infiltration of rainfall and from the bed of the streams. However, there is also some subsurface transfer from the limestone aquifers to the alluvium. Thus the primary waters of the alluvium, though all strong calcium carbonate types, shows more mineralization than the primary waters of the limestone-dolomite, the flysch or the shaley limestone aquifers. This relatively high mineral content occurs in alluvium waters low to very low in chlorine and sodium, and so free of any marine influence.

In four samples, two from Itea (Nos. 48 and 50) and two from Ghalaxeidon (Nos. 81 and 83), a beginning is seen of mingling with sea-water. This is much more marked in Nos. 47, 49, 52 and 65 from Itea, No. 82 from the borehole at Ghalaxeidon and No. 101 from a shepherds well between Itea and Ghalaxeidon. In these areas, the amount of NaCl does not increase steadily as the coast is approached; the highest NaCl content is found in those wells and boreholes which are pumped at the highest rate. This would seem to suggest that sea-water or brackish water extends far inland beneath the fresh water of the alluvium and that the uprising of the heavy mineralized water complementary to the drawdown of the come of depression is the mechanism whereby the NaCl content of the waters from the high-yielding wells is increased.

2.4. *Waters from the talus aquifers*

Springs are common from talus slopes, especially where the talus overlies flysch. While direct infiltration contributes to such springs during the winter, those which persist into summer and have permanent discharges must be fed by water from more extensive aquifers, mainly from the limestone-dolomites, but also from the flysch. Hence, it is to be expected that in chemical composition their waters must be related to those from the limestone-dolomite and flysch, and this proves to be the case.

All the 18 samples are carbonate waters, and while calcium is normally the dominant cation, in three samples (66, 140 and 147) magnesium is dominant. The calcium carbonate waters, with total soluble salts amounting to 324 ppm, are straightforward primary waters, and call for no comment, though in Nos. 56 and 118 there has been organic contamination resulting in high NO_3.

The three samples with high magnesium come from areas where the limestone-dolomite and the flysch waters are also high in magnesium. Thus, No. 66 is from a talus spring near the large spring at Elaion (Nos. 12 and 72) and a smaller spring (No. 67) all of which show high or highish magnesium. The other Mg-rich talus waters are connected with the overthrust Triassic dolomite of the Polidhroson-Amphiklia region, which is discussed in some detail in 3-1. Thus, the chemical composition confirms that the talus waters originate from the limestone-dolomite and flysch aquifers, since they vary as do these waters in different areas.

2.5. *Waters from the Conglomerate aquifer*

Tertiary and Quaternary conglomerates, composed essentially of pebbles and debris of limestone-dolomites, occur in some places, such as between Amphissa and Eratini, and behave like karstic dolomite-limestone aquifers; they also give rise to coastal springs. Thus three (Nos. 96, 99 and 128) are mingled with sea-water, so as to have a total soluble salt content of 10,018 ppm; the remaining three, on the other hand, contain but 268 ppm of salts, and are indeed less mineralized than the primary waters of the limestone-dolomite and flysch aquifers. Clastic sediments, derived from older sediments, are not infrequently less soluble than the matrix rock.

No. 77 is from the Pliocene conglomerate north of Itea, where coarse aquifer beds occur between clay aquicludes. No. 112 is from Lidhorikion, while No. 122 is from the Ayias Trias spring of Prosilion. No. 77 shows a slight trace of marine influence (Na and Cl in spray and precipitation) but the others are pure limestone waters. The three with admixed sea-water are contaminated to varying degrees, but exhibit no other marked peculiarity.

2.6. *Water from the Shaley limestone aquifer*

In the north-eastern area of Parnassos, the Lower Cretaceous shows a striking lithological change, the general limestone sequence changing laterally into an inter-bedded limestone-shale facies. These rocks have been tectonised, so that the shale beds show good cleavage and the limestone beds are jointed. The shale tends to act as an aquiclude, and the limestone as an aquifer; but en masse, the formation is more of an aquiclude, and upholds a watertable where the structure is favourable and so gives rise to springs. These may issue from the overlying Upper Cretaceous limestones, or from thicker limestone beds within the Lower Cretaceous.

Only one sample, No. 150, from this interesting series was available for inclusion in this study. It shows total soluble salts of but 203 ppm, and so is one of the least mineralized of all the 120 waters. It is almost completely a calcium bicarbonate water, with the 2 ppm of Na and the 7 ppm of Cl readily attributable to cyclic salts in the precipitation.

2.7. NO_3 *Contamination*

While the investigation has not extended to cover the bacteriological content of the waters, noticeable high (+ 0.50 meq., equivalent to + 31 ppm) NO_3 concentrations have been found in 9 out of the 120 samples. When it is found that all these waters are from springs or wells within, or on the edge of, villages and towns, there can be no doubt but that high NO_3 is indicative of organic contamination. For convenience in reference, the nine samples are listed here.

No. 6. Dhesfina Spring, in the village
No. 56. Spring in Amphissa town
No. 59. Open Well in Amphissa town

No. 60. Spring in Sernikaki Village
No. 61. Open well in Sernikaki Village
No. 83. Main well supplying Ghalaxeidon
No. 90. Main well, in centre of Tolofon
No. 93. Main well for Ayia Evthimia
No.118. Large spring within Khrison village.

Even if the total NO_3 reported in the chemical analyses is present in an inorganic form, high nitrates in domestic water supplies are dangerous in themselves. High NO_3 can cause methaemoglobinaemia or 'blue-blood' in babies. WHO (1958, p. 28) states «The ingestion of water which contains nitrates in excess of 50 to 100 ppm (as NO_3) may give rise to infant methaemoglobinaemia».

3. Ca:Mg RATIOS IN LIMESTONE-DOLOMITE AQUIFERS

Attention has been given to the Ca:Mg ratios of the pure waters issuing from the limestone-dolomite aquifers (33 samples) and to those waters from flysch aquifers (7) which have low Ca:Mg ratios. For these 40 samples the Ca:Mg ratios are shown graphically in Fig. 3, which also indicates the total soluble salts content of the waters.

Groundwaters whose total calcium and magnesium ions are derived by the solution of pure dolomite will have a Ca:Mg ratio of unity when expressed in milligram equivalents per litre units; when expressed in units of weight, the Ca:Mg ratio is 1:0.604. In a mixed dolomitic limestone, the calcite crystals are much more readily taken into solution than are the dolomite crystals. In laboratory experiments conducted separately on pure calcite and pure dolomite, with abundant CO_2, Thorpe (1932) reports that the solubility ratio of $2.CaCO_3$ to $CaMg(CO_3)_2$ is 1:0.28 by weight; according to Chilingar (1956) the ratio is 1:0.63 by weight. However, when both minerals are attacked at the same time by water with excess CO_2, the results of Bahre (1932) suggest that the calcite: dolomite ratio is 1:0.015 expressed in units of weight.

Accordingly, the maximum value of the Ca:Mg ratio (in meq. units) in waters from pure dolomite aquifers should be 1:1. If the Mg content is greater than the Ca content, the waters have obtained Mg from some other source. On the other hand, the Ca:Mg ratio of waters from mixed limestone-dolomite rocks may be anything less than unity, and the lower the Mg content, the more highly calcitic and the less magnesian is the carbonate aquifer. A rough division may be made at the point where the ratio is 1:0.3. From 1:1 to 1:0.3, the aquifer is a dolomite or dolomitic limestone; below the 1:0.3 ratio, the aquifer is a limestone.

3.1. *Limestone-dolomite waters enriched in magnesium*

Nine waters from limestone-dolomite show Mg in excess of Ca, and so lie in the zone entitled «Waters enriched in Mg from Serpentine» of Fig. 3. They come from four regions.

Five of the nine (Nos. 69, 70, 136, 143 and 148) are springs issuing from the overthrust Eastern Zone Triassic dolomite lying south of Polidhroson-Amphiklia. The dolomite is overthrust onto conglomeritic flysch, containing pebbles and grains of serpentine; the flysch is relatively impermeable and the springs issue from the dolomite-limestone just above the contact. Clearly, groundwaters formed in the Triassic dolomite with an almost equal content of Ca and Mg ions have been enriched further in Mg by contact with the serpentine of the flysch. There is no difficulty in explaining this water. The point of interest is that, for the 120 samples considered here, it occurs so intensively only in this one sub-area.

A few other dolomite/flysch contact springs in the area have also been sampled. No. 142 shows Ca:Mg as 1:0.82, and lies just outside the Mg-rich zone of Fig. 3. No. 138 is a sample of the same spring as No. 70, taken at a later date. No. 152 refers to a small contact spring just south of Eptalofon, also from Eastern Zone dolomite over flysch.

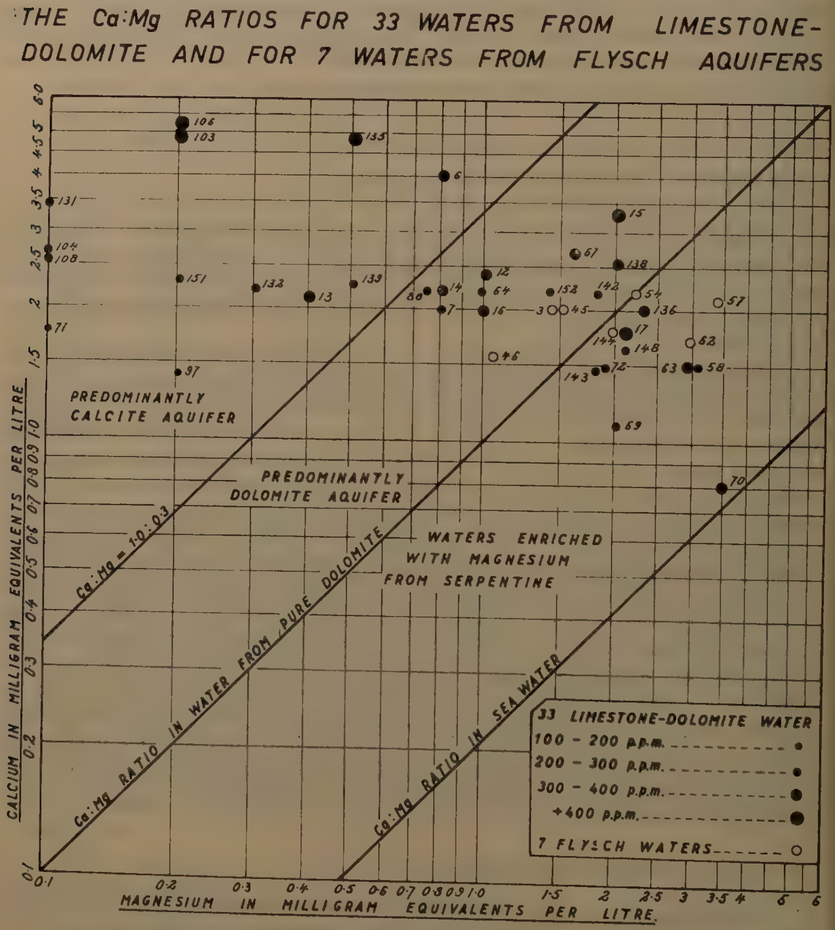


Fig. 3

The other areas of high magnesian content are of less general interest. Around Amphissa, Nos. 58 and 63 issue from small blocks of limestone overlying, or almost embedded in the upper, conglomeritic, flysch. However, other similar springs show a lower Mg content, and here the Ca:Mg ratio is less specifically diagnostic of the origin of the water. The large spring at Elaion (No. 72) shows Mg in excess of Ca on 12.7.60, but Ca in excess of Mg on 11.5.60. This spring is from Cretaceous limestones of the Eastern Zone overthrust onto flysch; possibly when discharge is high, the Mg obtained from the flysch is diluted so as not to cause any great overall increase in the Mg content. This spring is considered as typical of the region, and is being sampled repeatedly as opportunity offers.

The remaining sample, No. 17, in which Mg exceeds Ca comes from the Vlassis borehole. The borehole has been sunk through flysch to cut a large (slipped?) body of limestone totally enclosed in the flysch and outcropping along a ridge to the south of the village. Clearly, the water has been in close contact with the flysch, and its rather high mineralization (406 ppm) suggests that it has been in the rocks for a long time; the amount of annual recharge may be small.

3.2. *Limestone-dolomite waters with* Ca:Mg *ratio less than* 1:0.3

Eleven samples of water from limestone-dolomite aquifers show that the Ca:Mg ratio is less than 1:0.3, and so they lie in the zone entitled «Dolomite aquifer» of Fig. 3. However, they also embrace waters which have been enriched in Mg by contact with serpentine and ultra-basics, either as derived pebbles in flysch or in situ. They occupy five areas on the ground, though four of them are extensions of the areas just described in 3-2, and only one of them is entirely new, occurring in the south-west of the Parnassos-Ghiona Region.

Nos. 142 (1:0.82), 138 (1:0.78) and 152 (1:0.64) are the richest in Mg in this group, and come from the Triassic dolomite overlying serpentine-rich flysch in the area south of Polidhroson and Eptalofon. It is surprising not to find the main spring called «Manna» just south of Eptalofon included in the Mg-rich group. Of more importance is the fact that the main Lilaia spring, lying on the edge of the village, No. 14, with 1:0.33, has a comparatively low Ca:Mg ratio. It had been thought on the geological evidence that the Lilaia waters came from the main Jurassic (Tithonian) to Cretaceous (Cenomanian) limestones of the region. It appears to be an overflow spring at the limestone-alluvium contact; the presence of rather more Mg than would be expected indicates that the original theory will have to be checked very carefully.

Samples 15 (Mavromandalia) and 16 (Mavroneri) come from the eastern limits of the area. The great spring of Mavromandalia is from Cretaceous limestones, which overlie serpentine; hence a high Mg content is not unexpected. Mavroneri is also a major spring, and comes from a relatively small outcrop of Eastern Zone Triassic dolomite. Again, the high Mg content is to be expected, though the main problem here is to determine if the limited dolomite outcrop can supply all the water which issues from Mavroneri. These two spring lie just north of the Vlassis borehole, already described as high in Mg.

Around Amphissa again, the evidence from Nos. 58 and 63, already discussed, is supported by the highish content of Mg in No. 64, from limestone over conglomeritic flysch. The Elaion spring, from Eastern Zone Middle-upper Cretaceous limestones overlying flysch rich in serpentine pebbles, has already been noted as high in Mg on the evidence of Sample No. 72; this is supported by No. 12 from the same spring at a different date, and by No. 67 from a nearby, but smaller, spring.

Two samples comparatively high in Mg come from the south-west area. No. 7 was from a seepage from Upper Triassic dolomite of the Parnassos-Ghiona Zone, on the road beyond Ayia Evthimía. Yield is very small, and the water must have been in intimate contact with the dolomite. This water has most certainly not been enriched in Mg from ultra basics, and can be considered as a natural dolomite water. Its Ca:Mg ratio of 1:0.4 would indicate the solution of 3 calcite molecules for every 2 dolomite molecules. The other sample, No. 88, is from limestone over flysch, and is explained in the usual way by serpentine in the flysch.

3.3. *Limestone-dolomite waters with low magnesium content*

The remaining 13 samples from the 33 'unmixed' limestone-dolomite waters have low to nil Mg content; they may be considered as originating from limestone, and not dolomitic, aquifers and to have avoided all enrichment in Mg from ultrabasic rocks.

Many of them (Nos. 97, 102, 106, and 108), come from the limestones of the south-western portion of the area. Two come from the south-central portion, from Delphi and Dhesfina. The remaining six come from Lilaia, Eptalofon and Varyianni area, where they contrast strongly with the Mg-rich waters from the Triassic dolomite. In this important region, the Ca:Mg ratio can be of much help in distinguishing springs of different origin.

The fact that many of the proved limestone waters have a very low magnesium content should be borne in mind when studying the apparent disappearance of this ion in sea-water/limestone-water mixtures. The average composition used for «pure» limestone water may show more magnesium than is actually present in the water from the southern limestone aquifers which actually mingle with sea-water in the coastal areas.

3.4. *Relationship between* Ca:Mg *ratios and porosity of aquifer*

Chilingar (1956) has put forward some facts indicating a relationship between the Ca:Mg ratios of limestones-dolomites and their porosity, mainly with a view to studying their reservoir possibilities. In the Parnassos-Ghiona area, the limestone-dolomite springs appear to have a lower Mg content when their yield is higher in winter-spring. This appears to be due to shorter or less intimate content with underlying magnesium-rich flysch, and to have nothing to do with the porosity or permeability of the aquifer. Nevertheless, attention continues to be given to a possible relationship between yield and the dolomite-calcite ratio of the aquifer.

4. SEA-WATER CONTAMINATION OF GROUNDWATER FROM LIMESTONES

Of the 52 water samples from limestone aquifers, it was found that 19, from coastal areas, contained a high to very high content of soluble salts due clearly to an addition of sea-water to the groundwater. For several reasons, a careful study has been made of the problem of sea-water contamination of ground-water in the coastal aquifers of the Parnassos-Ghiona region.

4.1. *Object of study*

It is desired to tap and bring into use some or all of the groundwater of the limestones which is now rendered useless by mixing with small or large quantities of sea-water and is lost through coastal or submarine discharge from the aquifers, mainly karstic limestones. Such mingling appears to occur at some distance inland, and limestone springs at low elevations up to a kilometre or more from the coast, such as those of Kirra, east of Itea, normally contain a high content of total soluble salts. Hitherto, it has been assumed that mingling with sea-water has been the sole cause of this salinization of the groundwater; likewise, it has been assumed that the groundwater itself was normal, sweet (say 316 ppm) limestone groundwater before it mixed with the sea-water.

It was necessary to determine, as far as possible, what was the premixing composition of the groundwater, so that it could be seen whether or not it was suitable for use before attempting to tap it by drilling. The chemical investigation was also aimed at determining the percentage of sea-water in the mixed waters issuing from the coastal and submarine springs. Due to difficulties in determining the bromine content, this percentage has been determined by the chlorine content of the mixed waters; confirmation by a bromine analysis would have been of help. The study has also endeavoured to elucidate the changes in composition of the mixed waters, which it has been found, cannot be considered from the hydrochemical viewpoint as simple mixtures of varying percentages of sea-water and of the normal sweet (316 ppm) groundwater of the limestone-dolomite aquifers of the Parnassos-Ghiona Region.

4.2. *Presentation of data*

Table 1 gives the basic data on all waters, and the reference numbers of the 19 mixed waters from limestone aquifers will be found on Fig. 4; the average chemical composition of these 19 waters is, of course, shown in Table 3. There was no difficulty in distinguishing pure from mixed limestone waters; the highest total soluble

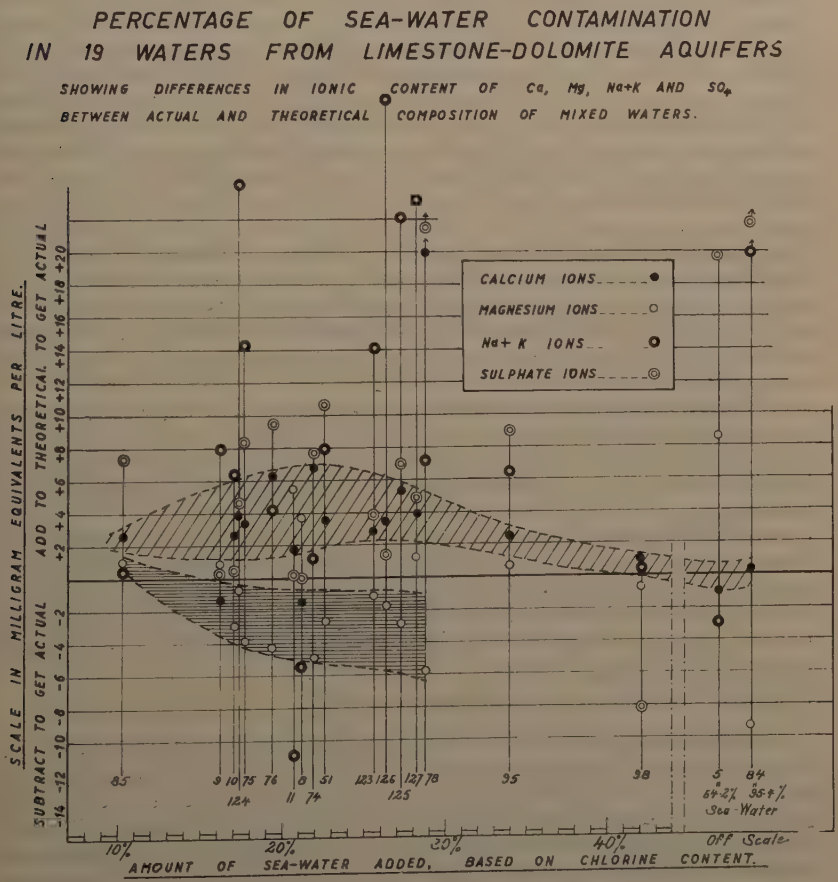


Fig. 4

salts content of a pure water was 476 ppm, from which it jumped to 4,776 ppm is the least mineralized of the mixed water.

The chemical composition of the sea water used was that determined from the mean of two analyses made on a sample (No. 100) collected off Ghalaxeidon on 22.8.1960. These analyses indicate that the major constituents amount to 39,071 ppm; this is some 5% higher than Dittmar's average, but as would be expected for a surface sample from a land-locked arm of the Eastern Mediterranean in August. The individual constituents were also checked against those of Dittmar's standard; it was found that the percentage increases were not quite uniform. This would indicate some error in analysis, since all authorities agree that the concentration, but not the ratios, may vary in sea-water. However, the errors would be standard ones for all the samples analysed, and their effects would tend to cancel out in the type of investigation made here. Nevertheless, to check the results, the more important calculations were made in duplicate using both Ghalaxeidon and Dittmar sea water (adjusted uniformly to Gulf of Corinth concentration) and no significant changes were introduced into the final results or conclusions. Accordingly, to prevent confusion, only the Ghalaxeidon water, as reported under Sample No. 100, has been shown in this study.

Table 4 shows the calculations made on Samples Nos. 10, 98 and 125, as well as on the average mixed limestone water of Table 3; similar calculations were made for the other 16 waters, but are presented only in part, and in graphical form, in Fig. 4. Nos. 10, 125 and 98 were selected at random, but so as to show varying amounts of admixed sea-water. The percentage of sea-water was accepted as the ratio of the Cl in the analysis (104.83 meq in No. 10) to the Cl (610.25 meq) in the standard Ghalaxeidon sea-water; a figure slightly below exact ratio was taken, to allow for the very small amount of Cl (0.265 meq) in the pure limestone water. Hence, in No. 10, 17.2% of sea water was calculated in terms of meq.; to this, 82.8% pure limestone water was added, also in terms of meq. The sum of these produced a 'Calculated Water' whose chlorine content of 105.18 meq. was just about equal to the 104.83 meq of Cl found for sample No. 10. The differences between the ions and anions of the natural and calculated waters were then found and reported as 'Ionic Differences'. Addition and subtraction symbols indicate whether the differences are to be added to, or subtracted from, the calculated waters so as to arrive at the natural waters.

A « + » sign accordingly indicates that the actual natural water contains that much more of the ion than would occur in a water made-up solely by a mixture of $Y\%$ sea-water plus $(100 - Y)\%$ pure limestone water; a « – » sign indicates that the natural water has lost as compared with a simple mixture of sea-water and pure limestone water.

The data is presented graphically in Fig. 4, which shows Ca, Mg, Na+K and SO_4 for all the 19 samples. The general zones within which the Ca and Mg changes may occur (positive for Ca and negative for Mg) are indicated. It was thought possible that there would be progressive changes as the percentage of admixed sea-water increased; the plotting presents but slight evidence of such progressive changes.

4.3. *Possible original composition of limestone groundwater*

The difficulty of the addition of Ca (4.37), Na+K (9.20), HCO_3 (1.07), and SO_4 (11.02), and of the subtraction of Mg (0.43), to/from the calculated water to form the Average Natural Water at the end of Table 4 would be overcome if it were assumed that the 70.8% aquifer water proved to be not 'pure limestone groundwater', but a water formed by the addition of the ions required for balancing to those provided by the 70.8% pure limestone water. The original water would of course have to be calculated by increasing the ions from the equivalent of 70.8% to 100.0%

TABLE 4

Determination of the ionic differences between some typical natural waters issuing as coastal or submarine springs from limestone aquifers and calculated waters with equal chlorine content formed by a mixture of the appropriate percentages of sea water and of fresh water from the limestone aquifers. All figures in milligram equivalents per litre.

Cations			Anions				Sample Number of Natural Water, or Nature of Mixture
Ca	Mg	Na + K	HCO_3	SO_4	NO_3	Cl	
4.05	20.33	85.07	0.54	9.20	0.07	104.96	17.2% Sea Water
2.01	0.98	0.38	2.88	0.17	0.06	0.22	82.8% L'ste Water
6.06	21.31	85.45	3.42	9.37	0.13	105.18	Calculated Water
8.80	18.40	91.92	4.40	9.89	0.01	104.83	Natural Water No. 10
+ 2.74	− 2.91	+ 6.47	+ 0.98	+ 0.52	− 0.12	− 0.35	Ionic differences
6.43	32.27	150.90	0.85	15.59	0.18	166.60	27.3% sea water
1.77	0.86	0.33	2.53	0.14	0.01	0.20	72.7% L'ste water
8.20	33.13	151.23	3.38	15.73	0.19	166.80	Calculated water
13.57	30.38	173.30	4.12	22.78	0.00	167.00	Natural water No. 125
+ 5.37	− 2.75	+22.07	+ 0.74	+ 7.05	− 0.19	− 0.20	Ionic differences
9.94	49.89	233.15	1.32	24.64	0.16	257.50	42.2% sea water
1.40	0.69	0.27	2.00	0.12	0.01	0.15	57.8% L'ste water
11.34	50.58	233.42	3.32	24.76	0.17	257.65	Calculated water
12.30	49.97	233.95	3.66	16.64	0.33	257.50	Natural water No. 98
+ 0.96	− 0.61	+ 0.53	+ 0.34	− 8.12	+ 0.16	− 0.15	Ionic differences
6.88	34.52	161.40	0.91	16.62	0.11	178.19	29.2% sea water
1.72	0.84	0.33	2.45	0.14	0.01	0.19	70.8% L'ste water
8.60	35.36	161.73	3.36	16.76	0.12	178.38	Calculated water
12.97	34.93	170.93	4.43	27.78	0.08	178.35	Average natural water
+ 4.37	− 0.43	+ 9.20	+ 1.07	+11.02	− 0.04	− 0.03	Average differences

to arrive at the true composition of the original groundwater of the limestone. This calculation has been carried out, and the chemical composition of this hypothetical water is given as follows:

	meq.	*ppm.*		*meq.*	*ppm.*
Ca	8.59	172	HCO_3	4.96	330
Mg	0.58	7	SO_4	15.74	756
Na+K	13.47	310	Cl	0.23	8
	22.67	489		20.93	1067

Such a water could not be brought into existance naturally under the hydrogeological conditions existing in the limestone aquifers of the Parnassos-Ghiona Region. A normal pure limestone water of the region would have to come in contact, and take into solution, appreciable quantities of Glauberite ($Na_2SO_4 . CaSO_4$) to achieve this hypothetical water. Glauberite is a mineral of the evaporite salt beds and could not have been formed, or continue to exist, in the Parnassos-Ghiona lithological facies. Wilder speculation is possible—Na as cyclic sea-salt (by why no Cl?), SO_4 by oxidation of pyrite occurring with bauxite (but why only in mixed waters?)—but it seems best to reject entirely the possibility of the existance of such a hypothetical groundwater in the Parnassos-Ghiona Aquifers.

The foregoing conjecture as to the aquifer water is possible since nowhere has it yet been possible to trace pure limestone groundwater and sample it as it is progressively mixed with sea water; hence on the landward side, conjecture is possible. From the seaward side, the admixture is known to be seawater, and no hypothetical composition is permissible.

4.4. *Ionic changes on mingling of groundwater and seawater*

Base exchange, precipitation, action of sulphur bacteria have been used (as in Kelley and Liebig, 1934; Foster, 1942; Burdon, 1953, p. 22) to explain changes in the chemical composition of coastal groundwater as it mingles with seawater in the aquifers. In general, the aquifers studied have been permeable sands and silts, with minerals suitable for base exchange; often sulphur bacteria may occur in them in association with organic matter. But along the Parnassos-Ghiona coast, the limestone water gushes forth freely from its karstic aquifers, which lack clay minerals and organic matter; likewise, it is clear that there is nil or negligible precipitation at, or around, the point of issue.

There would appear to be no clear explanation of why the natural waters contain much more Na+K and SO_4, and considerable more Ca, than would be present if they were simple mixtures of seawater and limestone groundwater. The loss of Mg is small, and may be due to replacement of Ca by Mg in the limestones immersed in the mixture; this type of dolomitization is not unexpected. Some of the increase in Ca and in HCO_3 may be due to increased solubility of the limestone in the mixed waters, though Rankama and Sahama (1949, p. 271) state «Compared with seawater, rainwater is remarkable for its strong leaching action on rocks».

However, the main problem is to account for the strong increase in Na+K and in SO_4. While the averages show + 9.20 meq. and + 11.02 meq. respectively, it is true that in some cases out of the 19, Na+K and SO_4 are negative. In Nos. 5, 8 and 11, Na+K are negative; in Nos. 8 and 98, SO_4 is negative. Neglecting these 4 exceptions out of the 19 samples, the case for unexplained increases of Na+K and of SO_4 is definite. It may be mentioned here that when Dittmar's seawater is substituted for Ghalaxeidon seawater, the increase of SO_4 remains substantially the same (+10.55 meq.), while the increase of Na+K is substantially greater (at +26.67) and still more difficult to explain. In fact, in this aspect of the work, this study poses a question rather than supplies an answer.

Turning for a moment to the four exceptions, Nos. 5, 8, 11 and 98, it must be recalled that in the first 44 analyses, Na+K were determined by difference and so possibilities of concealed errors must be taken into consideration. No. 5 refers to the submarine spring of Ay. Nicholas near Antikirra; recent mapping and some drilling under Dr. G. Aronis indicated a Maestrichtian limestone aquifer feeding water through an erosion gap in the flysch barrier into coastal talus-alluvium, whence it emerges as coastal-marine springs. No. 8 refers to a small spring in a limestone cave at the end of Ghalaxeidon harbour; sulphur bacteria may be active. No. 11 is the most southernly of the Kirra Spring group, and on no subsequent occasion did the calculation show the Kirra spring water as requiring negative Na+K correction (see Nos. 51, 123, 124, 125, 126 and 127). Finally, No. 98 refers to a coastal spring called «Vathithelli» near Eratini, approached only by boat and quite a normal spring far from human habitation or any obvious peculiarities.

Some of the karstic caves are inhabited by bats, and their droppings can affect the composition of the waters flowing through such caves. However, bats are not confined to, nor indeed have been noticed in, the coastal caves; nor does marine life gravitate towards such caves. A biological solution to the problem does not seem probable. Agricultural fertilizers can affect the composition of groundwater; but certainly the Greek farmers do not waste fertilizers on coastal limestone springs. The investigation has but revealed the presence of excess Na+K and SO_4 in these mixed waters; and explanation has yet to be found.

5. ACKNOWLEDGMENTS AND REFERENCES

5.1. *Acknowledgments*

The authors' acknowledgments are due to the Special Fund of the United Nations and to the Institute for Geology and Subsurface Research for permission to present this paper to the meeting; the work forms part of an investigation into the groundwater resources of the karstic limestones of Greece. The chemical analyses have been carried out by Miss A. Papastamataki in the laboratory of the Institute, while the Na and K determinations have been made at the Institute for Soils, Fertilizers and Climate, thanks to the courtesy of Dr. D. Catacousinos.

The authors have had the benefit of numerous discussions with their colleagues, in particular with Dr. G. Aronis and Mr. N. Papakis; but of course they take full responsability for the ideas advanced in this paper.

REFERENCES

BAHRE (1932) «Beitrag zum Themer Dolomitentstehung», *Zent. Minerelogie*, Vol. 46, Stuttgart.

BURDON, D.J. (1953) «The Underground Water Resources of Cyprus», Government Printer, Nicosia.

BURDON, D.J. and MAZLOUM, S. (1958) «Some Chemical Types of Groundwater from Syria», *UNESCO Symposium at Teheran*, October, 1958.

CHILINGAR, G.V. (1956) «Use of Ca:Mg Ratio in Porosity Studies», *Bull. Amer. Assoc. Petrol Geol.*, Vol. 40, pp. 2489-2493.

DITTMAR, W. (1884) Challenger Expedition Report, *Physics and Chemistry*, I, 203.

DUROV, S.A. (1948) «Classification of Natural Waters and Graphic Representation of their Composition», *Akad. Nauk., SSSR*, Vol. 59, pp. 87-90.

FOSTER, M.D. (1942) «Base-Exchange and Sulphate Reduction in Salty Ground Waters along the Atlantic and Gulf Coasts», *Bull. Amer. Assoc. Petrol Geol.*, Vol. 26, No. 5, pp. 838-851.

GORHAM, E. (1955) «On the Acidity and Salinity of Rain», *Geochimica et Cosmochimica Acta*, Vol. VII, pp. 231-239.

KELLEY, W.P. and LIEBIG, G.F. (1934) «Base-Exchange in Relation to Composition of Clays, with Special Reference to Effect of Sea-Water», *Bull. Amer. Assoc. Petrol Geol.*, Vol. 18, pp. 358-367.

RANKAMA, K. and SAHAMA, T.G. (1949) «Geochemistry», Univ. of Chicago Press, Chicago 37.

THORPE (1930) Dictionary of Applied Chemistry, Third Edition.

TWENHOFEL, W.H. (1950) «Principles of Sedimentation», McGraw-Hill, New-York.

W.H.O. (1958) «International Standards for Drinking-Water», World Health Organization, Geneva.

Institute for Geology and Subsurface Research, 1959/60. 1:50,000 Geological Map of Greece, Sheets for Amphissa, Parnassos and South Parnassos.

LA FLUOROSE DENTAIRE NATURELLE D'ORIGINE HYDRIQUE, OBSERVÉE CHEZ LES HABITANTS ET LES ANIMAUX DOMESTIQUES DE LA RÉGION DE LAURIUM. SON ANATAGONISME POUR LA CARIE DENTAIRE.

J. CAMINOPETROS et M. PERTESSIS

La fluorose dentaire fut trouvée endémique pour la première fois en Grèce par nous chez les habitants de la ville de Laurium et de villages voisins p.ex. Camariza, excepté le village ouvrier de Placa, où les enfants sont trouvés indemnes de fluorose.

La présence de fluorure de calcium dans les eaux des puits de la ville de Laurium et de la campagne jusqu'au cap de Sounion, constatée aussi pour la première fois en Grèce, avait prouvé l'origine hydrique de la maladie.

Le taux du fluor provenant de fluorure de calcium dans l'eau des deux puits profonds de la ville de Laurium, atteint pour celui de la ville centrale, de 35 m. de profondeur, 3,3 mg. au litre et pour celui de la partie N—E, de 108 m. de profondeur, 1,7 mg. au litre.

Dans le village Camarisa dans deux puits superficiels, 4 et 5 mètre profonds le taux fut à 3,8 et 4,1 mg. au litre

A Legrena, partie S—E au delà du cap Sounion, 2 puits examinés ont donné un taux de 2,2 mg et 0,5 mg de fluor par litre d'eau.

Par contre dans l'agglomération ouvrière de Placa le taux de fluor dans le seul puits de la région ne dépasse pas 0,5 mg.

Le degré de la fluorose dentaire, déterminé en collaboration avec plusieurs dentistes chez les écoliers de la ville Laurium à partir de l'âge de 7 à 19 ans, est en proportion directe avec le taux de fluorure de calcium dans l'eau potable.

Par contre la carie dentaire est en proportion inverse de l'apparition de la fluorose ainsi que du taux du fluorure de calcium dans l'eau potable.

La présence de la carie dentaire atteint un pourcentage de 26 dents cariés pour 100 à Athènes chez les écoliers de 14 ans tandis que dans la ville de Laurium il ne dépasse pas le nombre de 4%. Il faut signaler à côté de ce fait, un autre, que nous avons été amenés à constater dans les villages agricoles de la plaine de Mesogée, Coropie et Marcopoulo. Il s'agit de l'abaissement de la fréquence de la carie dentaire, constaté chez plus de 500 écoliers de ces villages. Le pourcentage observé fut exactement inférieur à 4%, c'est-à-dire celui de la ville de Larium tandis que l'eau potable dans ces villages est totalement dépourvu de fluorure de calcium.

Ce fait peut être attribué à la bonne alimentation des habitants, due à la bonne production agricole de cette région.

Par contre le rôle de la sous-alimentation, existant chez les ouvriers de Laurium pour la carie dentaire est souligné par le cas du village Anavissos, côte S—E du Golfe de Saronique.

Ce village présente la particularité de l'inégalité du taux de fluorure de calcium dans le grand nombre des puits de ce village (60 puits qui sont en majorité superficiels). La carie dentaire se présente de beaucoup plus élevée chez eux qu'à Marcopoulo et Coropi aussi bien parmi les enfants atteints de fluorose dentaire que parmi les enfants indemnes d'elle.

Des récentes expériences de la reproduction de la fluorose dentaire en usant la poudre de fluorure de calcium par voie orale chez le chien, le rat blanc et la poule ont souligné l'absence de toxicité de ce sel surtout pour la poule et le chien, à l'encontre du fluorure de Sodium.

Ces expériences nous ont apporté de renseignements sur la morphologie des besoins dentaires chez le chien et le rat blanc.

SYMPOSIUM ON HISTORY OF DEVELOPMENT OF WATER SUPPLY IN AN ARID AREA IN SOUTHWESTERN UNITED STATES SALT-RIVER VALLEY, ARIZONA (¹)

**H.E. SKIBITZKE, R.R. BENNETT, J.A. DA COSTA,
D.D. LEWIS, and T. MADDOCK, Jr.**

Préface by H.E. Skibitzke

The purpose of this paper is to describe the history of development of water supply in an arid area in Arizona is the southwestern United States, an area of rapid population growth and accompanying extensive development of both ground- and surface-water supplies.

Although the general features of water occurrence throughout the arid part of Arizona are described briefly, the paper, consisting of five sections, is directly concerned with the hydrologic system in the Salt and lower Gila River Valleys in the general vicinity of Phoenix.

The first section is a historical review of the activities of man in the area with particular reference to water-supply development. In a general sense there have been two civilizations in the area; first, the prehistoric Indians who after several centuries of occupation apparently were not able to cope with the water problems they had created, and accordingly, abandoned the area; and secondly, the present civilization beginning about the middle of the 19th century.

The second section, which covers the early period of modern water-supply development in the area, is concerned primarily with the surface-water resources and the construction of the large irrigation systems. The storage and transportation of surface water converted substantial areas in the barren desert to some of the most productive farmland in the world.

The third section is concerned with an intermediate period of water-supply development during which the interrelationships between the surface- and ground-water systems became apparent. The application of large quantities of surface water resulted in water-logging problems, but it was found these could be solved effectively and efficiently by the pumping of ground water. Morever, it also became apparent that shallow ground water rather than being a troublesome problem was a valuable resource and thus the large-scale development of the ground-water resources and expansion of irrigated areas began.

The fourth section, considered to cover the modern period (1940-1961), described the significant controlling factors involved in the extensive development of the ground-water resources. Although the quantity of stored ground water is tremendous, there are geologic features that limit the availability of this water. Moreover, the recharge rate is negligible compared to the pumpage; hence, it is apparent that high rates of pumping cannot continue indefinitely. Just what changes in water development and use will occur in the future is problematic. At present the area is tending toward a more complex economy in which some agricultural land is being replaced by urban developments which consume less water.

The final section summarizes the history of water development and describes the principal hydrologic problems involved in the management of water resources in the area.

Most of the hydrologic data used in the preparation of the symposium was obtained through the water-resource studies by State and local agencies in cooperation with the U.S. Geological Survey. The writers are especially indebted, however, to the Salt River Valley Water Users' Association, Phoenix, Arizona, who furnished a considerable amount of records and other data.

The maps showing the locations of the prehistoric canals (fig. 4 and 10) were taken from a map furnished by Donald H. Hiser, Architect, Phoenix.

The various sections of the paper were prepared primarily by different authors, but in order to reduce repetition and provide better continuity, parts of some sections were deleted and others transposed. Thus autorship of the sections cannot be closely identified, however, the principal responsibility is as follows: (1) Historical Review —J.A. da Costa, (2) Early Period—Surface Water Development—D.D. Lewis, (3) Intermediate Period—Interrelationships of Surface and Ground Water— R.R. Bennett, (4) Modern Period—Ground-Water Development—H.E. Skibitzke, (5) Summary—T. Maddock, Jr.

(¹) Publication autorized by the Director, U.S. Geological Survey

HISTORICAL REVIEW

Long before man appeared on Earth, in Tertiary time, when uplifting created numerous valleys and basins that have been partly filled with material eroded from the highlands, the first chapter in the hydrologic history of southwestern Arizona was written. A hydraulic equilibrium in which discharge of water from the basin equaled recharge prevailed until man entered the area and disturbed the hydrologic system by digging the first irrigation ditch for the diversion of water.

Since that time events of hydrologic significance have followed each other in rapid sequence. It is the history of the hydrologic events, which are intimately related to the human activity in the area, that are chronicled in this historical review.

Although this paper refers in general to the southwestern part of Arizona, the area with which it is most concerned consists of the hydrologic basin that includes the Gila and Salt River valleys from their headwaters to Gillespie Dam, especially the Salt River valley in the vicinity of Phoenix. (See fig. 1).

Arizona may be divided into three water provinces, which in general coincide with the physiographic provinces: the Basin and Range Lowlands, the Central Highlands, and the Plateau Uplands. (See fig. 2.) The Basin and Range Lowlands, which cover approximately the southwestern half of the State is a desert region consisting of broad gently sloping alluvial valleys separated by relatively disconnected mountain ranges. The precipitation there ranges from about 2 to 27 inches (50-700 mm); the average is about 10 inches (254 mm). (See fig. 3.) The alluvial valleys, which in part are underlain by thick sections of water-bearing material, contain the principal areas of fertile land that through irrigation have been the site of a highly developed agricultural economy. The Central Highlands is a mountainous region trending northwest across the central part of the State. The high mountains force the air masses, primarily moving from the west, to rise, thereby cooling and condensing them to produce precipitation. This precipitation which ranges from about 10 to 31 inches (254 to 787 mm) a year, runs off to form perennial streams, many of which flow westward onto the desert area.

The collection of precipitation data in Arizona began in 1866 at Fort Mc Dowell, near Phoenix, and by 1897 there were 17 stations in the Gila River basin. At present there are about 310 precipitation stations in the State, some of which have been in operation continuously for more than 60 years. Table 1 summarizes the climatological data for Phoenix and Prescott, whose climates typify the desert and mountain regions respectively.

Evidence suggests that man appeared in Arizona as early as 15,000 years ago. Attracted perhaps by the abundance of game, the earliest Arizona settler was mainly a hunter. It was not until the Hohokam Indians appeared in the area, possibly as early as 500 B.C., that man began to use water in farming and began the disturbance of the equilibrium of the hydrologic system.

The Hohokam Indians seem to have settled primarily in southwestern Arizona from about 500 B.C. to 1400 A.D. Their first irrigation works were developed during the latter phases of their civilization, possibly before 1100 A.D. There are also indications that some surface water was used earlier; this, however, seems to have been by the spreading of flood water rather than by diversion by irrigation canals. Crops were planted in the mud left by the receeding floods, a method similar to that used in prehistoric times in the Nile River Valley and in the Negev region of Israel and still used today by the Papago Indians in sourthern Arizona. In the Negev region, where in some places the rainfall is less than 3 inches per year, the ancient Hebrews utilized the clay layers in river channels. Water absorbed during wet periods could be retained for long periods of time and later used for growing crops.

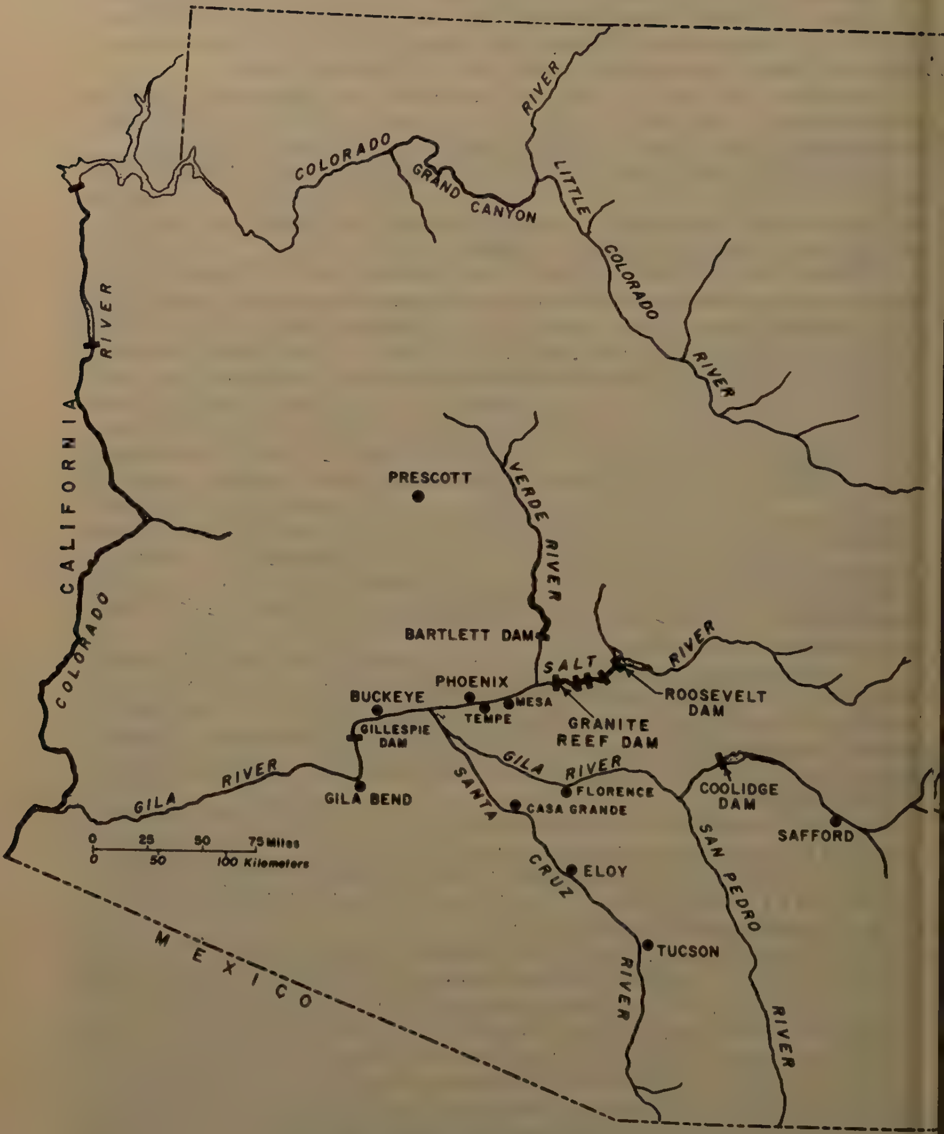


Fig. 1 — Map of Arizona showing place names.

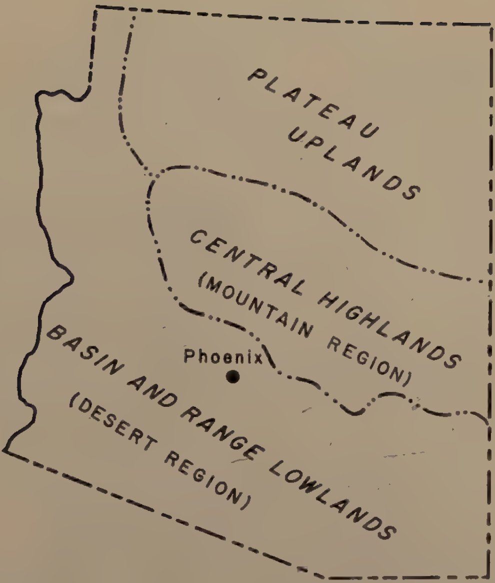

PLATEAU UPLANDS
CENTRAL HIGHLANDS (MOUNTAIN REGION)
Phoenix
BASIN AND RANGE LOWLANDS (DESERT REGION)

Fig. 2 — General water and physiographic regions of Arizona.

It is conceivable that similar methods may have been used by the Hohokams in the period before the introduction of more advanced irrigation practices.

Hohokan irrigation reached a peak between 1200 and 1400 A.D. The fact that their canal system was built with adequate slope does not, however, indicate that it was a fixed system. The Hohokams dug several canals each upslope from the proceding ones. The final canal, built on almost the same alignment as the present-day Arizona canal, had an almost flat gradient and apparently was a failure.

The main prehistoric canal systems in southwestern Arizona were in the Salt River valley in the region surrounding the present city of Phoenix. (See fig. 4.) H. R. Patrick of Phoenix explored the Salt River valley from 1878 to 1903 and surveyed the lands around Mesa, Tempe, and Phoenix. In the course of this work he surveyed and drew the first map of the prehistoric Indian canals. Other historians and explorers have published maps of the old canals; these maps show that some of the modern canals follow the old alignments. The parallelism of the recent and ancient canals shows that the gradients of the old canals were similar to those of the modern works.

The longest of the old canals spanned a distance of 12 miles (19 km); about 28 miles (45 km) of mains have been identified in canal systems. A total of more than 175 miles (282 km) of Hohokam canals have been mapped, but vestiges of old canals are constantly being discovered especially during excavation for water and sewage lines. Parts of the canals are still visible, and in such places their depth is about 27 feet (8 m). Estimates have been made that perhaps as much as 240,000 acres (97.00 ha) were at one time under irrigation in Arizona. Many of the prehistoric irrigation canals were of large dimensions even by present standards, for in some places the main canals were as much as 50 feet (15 m) wide at the bottom, 75 feet (23 m) wide at top, and 30 feet (9 m) in depth. Maize, squash, and beans were the first crops grown by the prehistoric Indians; later, irrigation enabled them to increase the variety of crops, and cotton and varied types of beans and maize were added.

TABLE 1

Average Temperatures
(Long term means, Phoenix—24 years of record, Prescott—18 years of record)

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Ann.
Phoenix (Airport)	°F	49.7	53.3	59.9	67.1	75.5	83.9	90.1	88.3	82.7	70.8	58.4	52.1	69.4
	°C	9,7	11,8	15,5	19,5	24,2	28,8	32,3	31,3	28,2	21,6	14,7	11,2	20,8
Prescott (Airport)	°F	35.3	39.4	44.8	52.9	60.9	70.1	76.0	73.9	68.2	57.0	45.6	37.8	55.2
	°C	1,8	4,1	7,1	11,6	16,1	21,2	24,4	23,3	20,1	13,9	7,6	3,2	12,9

TABLE 1 *(continued)*

Total Precipitation

(Long term means, Phoenix—24 years of record, Prescott—18 years of record)

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Ann.
Phoenix	in.	.60	.82	.66	.35	.17	.06	.70	.90	1.00	.40	.47	.97	7.19
(Airport)	mm.	15,2	20,8	16,8	8,9	4,3	1,5	17,8	25,1	25,4	10,2	11,9	25,6	182,6
Prescott (Airport)	in.	1.10	1.38	.98	.80	.30	.23	2.71	3.70	2.16	.68	.62	1.37	16.03
	mm.	27,9	35 1	24,9	20,3	7,6	5,8	68,8	94,0	54,9	17,3	15,7	34,8	407,2

TABLE 1 *(continued)*

Total Evaporation (Average)
(Long term means, Phoenix—24 years of record Prescott —18 years of record)

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Ann.
Bartlett Dam	in.	4.09	4.50	7.10	10.43	14.55	17.03	17.23	14.50	12.70	9.25	6.06	4.19	121.63
	mm.	103,9	114,3	180,3	264,9	369 6	432,6	437,6	368 3	322,6	235,0	153,9	106,4	3089,4
Roosevelt Dam	in.	1.83	2.66	4.90	7.16	10.42	12.25	12.28	10.26	18.10	5.33	2.87	1.81	80.87
	mm.	46,5	67,6	124,5	181,9	264,7	318,8	327,2	260,6	459,7	135,4	72,9	46,0	2054,0

From: Climatological Data, Arizona, Annual Summary, 1960: U. S. Department of Commerce, Weather Bureau.

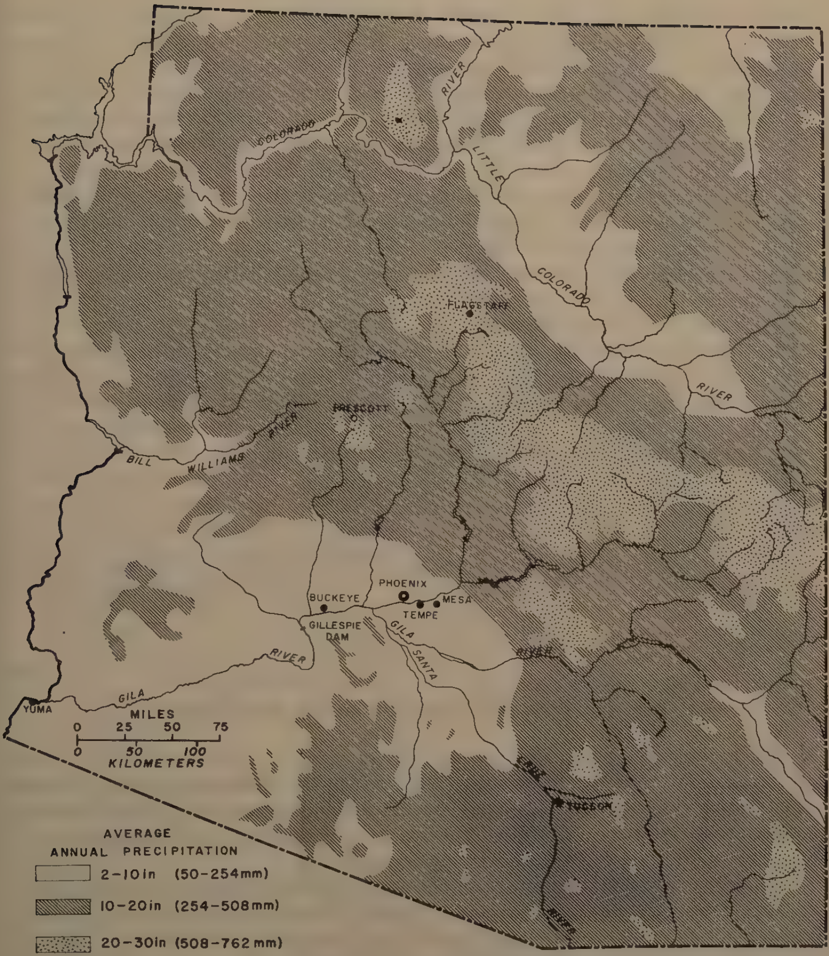


Fig. 3 — Distribution of precipitation in Arizona.

In the early part of the 14th century, the Salado people moved from the mountains into Hohokam lands, possibly because of the great droughts of 1276-1809 which are indicated from tree-ring analysis. At some time before 1400 the farm lands probably became waterlogged due to a rising water table and doubtless, after centuries of use, all the arable land was exhausted and laden with alkali left by the evaporation of irrigation water. Around 1400 A.D. the Hohokam culture appears to have vanished. After living in the southwestern Arizona desert for more than a thousand years, and reaching a relatively advanced cultural state, the Hohokams passed into oblivion.

When the first Spanish explorers entered southwestern Arizona in 1539, they encountered only a few Pima Indians, who were making use of irrigation in small scale by diverting water directly from the streams onto their fields. Their general

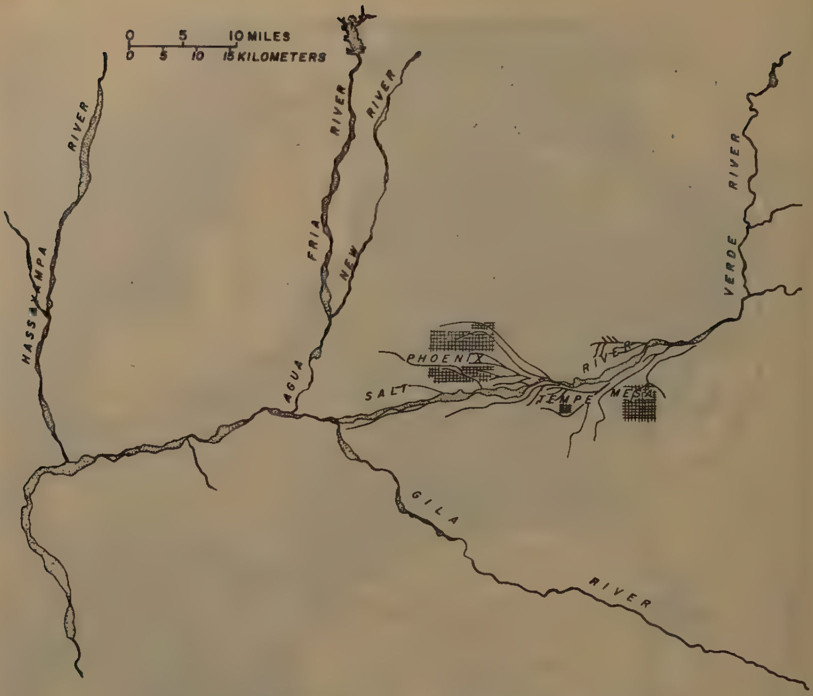


Fig. 4 — Prehistoric canals in the Salt River valley.

cultural level was much more primitive than that of the Hohokam people. Although there is some evidence that the Pimas are descendants of the Hohokams, the Pimas themselves always speak of the Hohokams as a vanished race. («Hohokam» is a Pima expression meaning «those who have gone»).

Prehistoric Indian irrigation practices were not limited to the Salt River valley, for there is evidence of several irrigation systems in the Gila River valley, although they are not as extensive as those in the Salt River valley. The canals in the Gila River valley area were mapped before the development of the modern canal systems, hence a good record of them was obtained. The larger of the prehistoric canals there was traced for more than 20 miles (32 km). The canal development indicates that there must have been several thousand acres under irrigation in this area.

Other ancient water-distribution works existed from the junction of the Gila with the Colorado to near the source of the Gila and also along the Verde River. Many other prehistoric irrigation systems probably existed in other river valleys of south central Arizona, but their remains have been obliterated by the irrigation development of modern man.

The first Spaniards arrived in Arizona in 1539 and in 1691 Father Eusebio Kino entered Arizona to begin a saga of missionary effort that contributed notably to the development of civilization in the southwestern parts of the state. During the 25 years in which he journeyed over the southwestern United States he traveled at least 14 times into southwestern Arizona from his headquarters in Mexico, 125 miles (201 km) southeast of Tucson. His explorations included the Gila valley to the confluence with the Colorado River. Father Kino pioneered Arizona's livestock industry by supplying the Indians with cattle, sheep, goats, and horses, and encouraged agriculture by introducing new food plants to the Indians.

Nearly 150 years later, during the period of Mexican control of Arizona (1823-1848), the first American pioneers entered Arizona and in 1846 Lt. Emory, on a military expedition down the Gila to its mouth and into California, described the Pima Indian irrigation works in the Gila River valley.

By the Treaty of Guadalupe-Hidalgo of 1848, all of Arizona north of the Gila came into possession of the United States, and thus began the period of American occupation and development. Even before President Lincoln signed the act creating the Arizona Territory in 1863, the development of Arizona's water resources by white settlers had started. Oliver Meredith Wosencraft in 1849 proposed the irrigation of the Imperial Valley in California and in 1859 the first water-powered flour mill was in operation in Tucson. The Mormons were the first modern men to use irrigation in southwestern Arizona. In the early 1860's they settled at Mesa in the Salt River valley and in the vicinity of Safford and other localities in southern Arizona.

The drilling of the first wells was made possible by the technological advances of the late 1800's. Some impetus to this development may have been provided by the several severe droughts that afflicted Arizona in the 1800's; the most severe extended from 1820-1823, and from 1896 to 1904. To encourage the drilling of artesian wells the legislature in 1875 offered a reward of $3,000 to the first person discovering artesian water in the Territory. This reward was not paid until 1883 when C.C. Whitney claimed it for an artesian well drilled near Pinal, 15 miles northwest of Coolidge Dam.

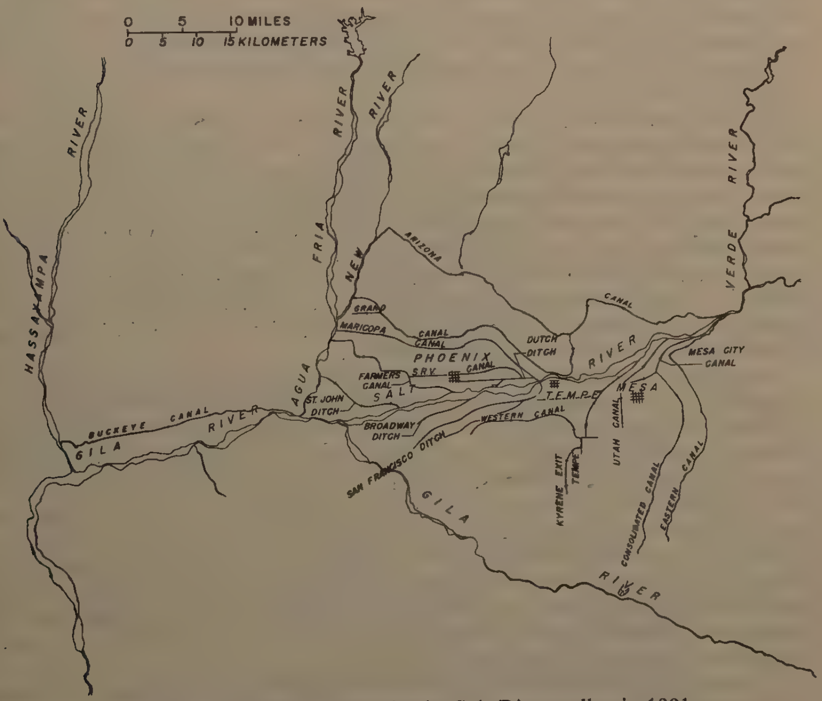


Fig. 5 — Irrigation canals in the Salt River valley in 1901.

The first diversion of water from the Salt River by American settlers was made in 1867 when water from the Jack Swilling ditch, later called the Salt River canal, was spread over a few acres of land and a crop was harvested. This was followed by the building of the first canal (Maricopa Canal), and by 1884, 35,000 acres (14.200 ha) were under cultivation in the Salt River valley and a total of 80,000 acres (32.400 ha) throughout the Territory. More than 132,000 acres (53.500 ha) were under irrigation in the Salt River valley by 1902, when the Congress of the United States passed the Reclamation Act. (See fig. 5.) This Act provided the funds for construction of the dams needed to insure more water for irrigation.

The first major storage reservoir in the Salt River valley was Roosevelt Dam, completed in 1911, one year before Arizona became the 48th State. Roosevelt Dam is still the largest capacity dam in the area. Later three additional dams were constructed on the Salt River and two were built on the Verde River.

The first water developments in the Salt River valley were made by private individuals. Although the water-resources investigations were carried on in the late 1800's by the Federal Government, the advent of statehood in 1912 and the increasing legal entanglements over water made it apparent to the state that certain legislation and additional evaluation of the water resources were necessary for their development. In 1912 the State legislature passed an act providing for cooperation with Federal agencies primarily for an expanded stream measurement program, but also for ground-water studies.

The widespread use of irrigation water in an area where the water table was relatively close to the land surface resulted in widespread waterlogging. Drainage problems increased in severity in the Salt River valley for several years because of continued application of irrigation water, which raised the water levels in the western part of the valley. Extensive drainage problems were solved when large-scale ground-water development caused the water table to decline. This decline has continued to the present time, except in a few small fringe areas where the water table remains at shallow depth.

By 1919 a State Water Code Act had been adopted, which created the office of State Water Commissioner. Later, in 1943 the duties of the State Land Commissioner were combined with the duties of the State Water Commissioner and the Land and Water Department started operating as a unit. In 1939 the State legislature appropriated funds for expanded investigations of the ground-water resources of the State through cooperative agreements for water-resources studies between the State Water Commission and the U. S. Geological Survey. The work done by the U. S. Geological Survey under the cooperative program includes the collection of basic hydrologic data, geologic and ground-water investigations of individual areas, and studies concerning specific hydrologic problems.

The main irrigation project in the Salt River valley is the Salt River Project, organized in 1917, which serves about 239,000 acres (97.000 ha) of irrigable land, and has a total of about 2 million acre-feet (2.47 millions m^3) of storage capacity in surface reservoirs. Within the 1,000 square miles (2.590 km^2) of the Salt River Project are a total of 1,400 miles (2.250 km) of canals and laterals. In the Salt River valley are four other principal irrigation-service areas called Districts. These are public agencies and locally operated; their combined area is about 131,000 acres (53.000 ha). The remainder of the valley area is served with water by private individuals or firms. Along the east border of the Salt River Project the Roosevelt Water Conservation District, south of Mesa, was formed in 1920. It occupies an area of approximately 37,000 acres (15,000 ha). Its main source of supply is from wells within the District, but it also receives Salt River Project water.

The Roosevelt Irrigation District in the vicinity of Buckeye, occupying 38,000 acres (15.400 ha), was organized in 1923. The District obtains all its water from wells.

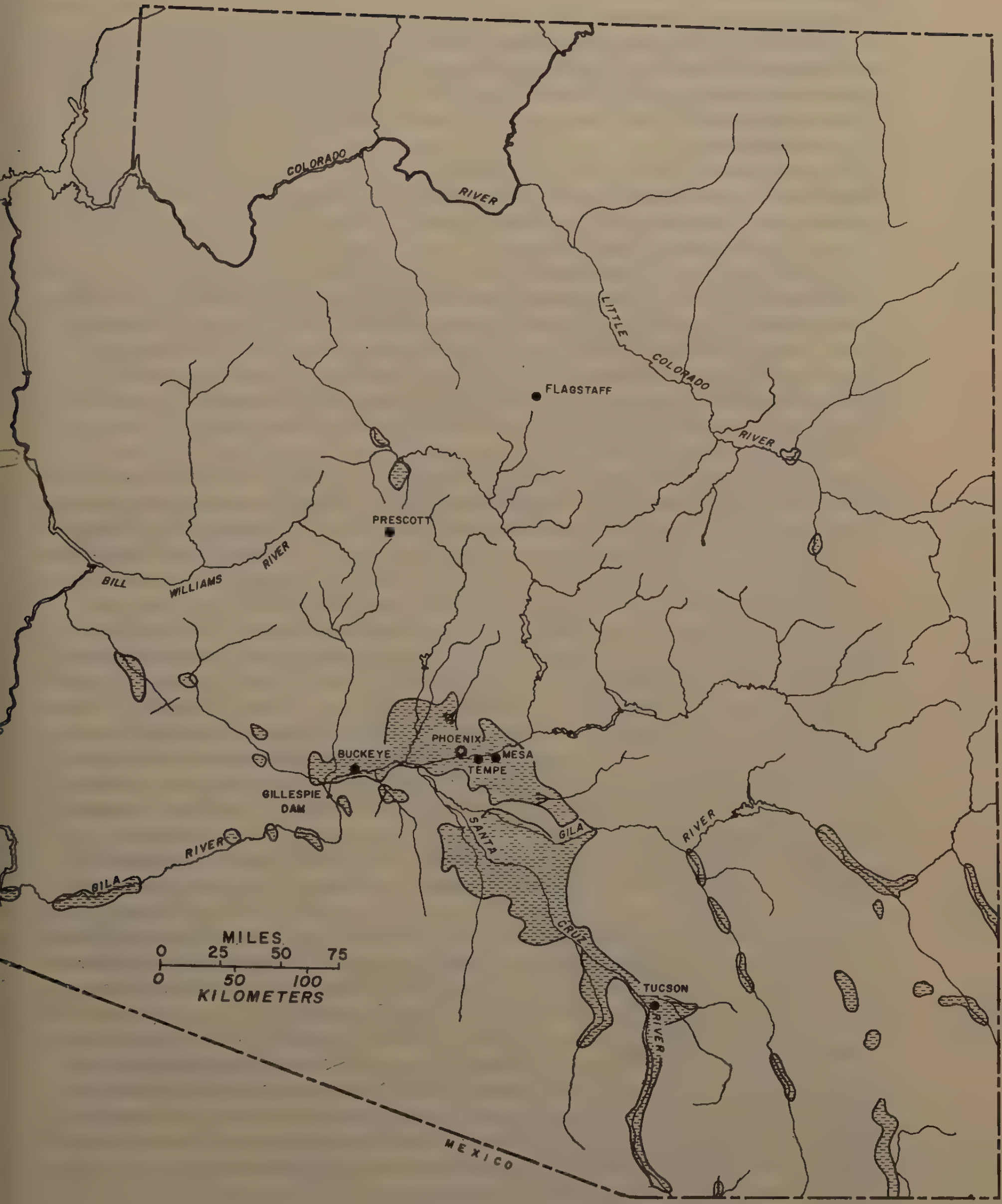


Fig. 6 — Principal areas of ground-water development.

The Buckeye Irrigation District covers over 18,000 acres (7.290 ha). Its water supply is obtained partly from the Salt River Project and partly from about 45 pumped wells.

Electric power from the Colorado River became available to the city of Phoenix in 1940 and in that same year ground-water withdrawals increased greatly. The rapid decline of ground-water levels became of concern to the State authorities and a series of legislative measures followed. In 1945 legislation was passed requiring registration with the State Land Commission all wells of more than 100 gpm (6.3 lps) discharge.

A law (ground-water code) was established in 1948 declaring as critical all ground-water areas in which water levels had declined seriously and overdevelopment was apparent. Four areas were declared critical—two in the Salt River valley and two in the lower Santa Cruz valley.

In 1952 a State Underground Water Commission was created to «make a comprehensive study of the source, extent, and nature of the underground waters of the State of Arizona». The Commission recommended the enactment of appropriate ground-water legislation to provide «equitable apportionment of water among all present users in overdeveloped areas». The Commission also recommended that further development of new land using ground water for irrigation be prohibited in certain areas and that provision be made for closing other areas when the availability of water became critical.

In 1953 some Arizona land, mostly in areas bordering the mountains, began going out of cultivation due to lack of ground water. Urbanization, especially in the Phoenix area, has also taken some land out of production. This, however, is largely compensated for by new agricultural developments which increase the total area under cultivation. Thus, the irrigated area in the Salt River valley has grown from about 35,200 acres (14.300 ha) in 1889 to 250,000 acres (101.000 ha) at present.

Since Americans first occupied the state, a little more than 100 years ago, the development of ground-water supplies in Arizona, particularly in the southwestern desert part, has been extensive. In 1878 there were only 41 wells in Pinal County; a mere 5 wells were completed in Maricopa County from 1889 to 1895. Today there are more than 2,500 wells in the Sallt River valey alone and about 6,000 in all Arizona.

The total amount of water used for irrigation in the State and increased from 5,200,000 to 6,500,000 acre-feet (6.31 to 8.02 millions m^3) just in the past decade. Of this amount a total of 4,700,000 acre-feet (5.797 millions m^3) or about 70 percent is ground water. (See fig. 6.)

After the second world war, the national trend toward greater travel coupled with a healthy climate and agressive promotion resulted in the enormous growth of the area.

The population ot Arizona has doubled every 10 years for the past 40 years. The population of Maricopa County, where Phoenix, the State capitol, is situated, has increased from 35,000 in 1910 to more than 650,000 in 1961, and current forecasts indicate that the population will double in the next decade.

In the short period of about 50 years the Salt River valley area in the vicinity of Phoenix has experienced a great change. From a relatively austere desert farming economy it has been transformed into a highly developed and complex economy in which industry, recreation, tourism, in addition to agriculture, are important factors in the economic structure. The conversion of the barren desert to the rapidly growing community of today would not have been possible without ample water and its future is likewise so dependent.

2. THE EARLY PERIOD—SURFACE-WATER DEVELOPMENT

The surface-water resources in Arizona are highly variable, both with respect to time and their areal distribution. In general the yearly precipitation in the state amounts to about 80 million acre-feet (987.000 million m^3), but because of the high rate of evapotranspiration only a small percentage—5 to 10 percent—of this amount runs off as streamflow. Most of this runoff occurs in the Central Highlands, an area composed of hard rocks forming a rugged mountainous terrain. The relatively high rate of precipitation there (10 to 30 inches annually) gives rise to perennial streams, most of which flow to the south and west into the alluvial valleys of the Basin and Range lowlands province, where the precipitation is small. Fig. 7 shows diagramatically the average yearly discharge of the principal streams of the state. The streams with the largest flow, and the ones of most interest to this symposium, are the Salt River, extending eastward from Phoenix, and the Verde, extending northward from its junction with the Salt River. The Salt and Verde Rivers join a few miles east of Phoenix and then flow westward through the narrow Salt River gorge east of Phoenix. The Salt River joins the Gila River about 15 miles west of Phoenix.

The drainage area of the Salt River and the Verde River above Granite Reef Dam (see fig. 1) is about 13,000 square miles; the Salt River having a drainage area of about 6,300 square miles and the Verde about 6,700. The area drained by the Salt River is extremely rugged and mountainous. The western boundary of the Salt River basin where the river emerges from the Central Highlands is at an elevation of about 1,325 feet (at Granite Reef Dam); the highest elevation in the basin is 11,400 feet in the extreme eastern part. The elevations in the Verde basin range from approximately 1,450 feet at the mouth of the river to more than 12,000 feet in the northern part.

The climate in the mountainous region of the Salt and Verde River basins is also quite variable, for the winters when snowfall prevails, are long and the summers, characterized by heavy showers, are short.

The runoff in the Central Highlands is highly variable but in the Salt River basin it averages about 2.8 inches (71 mm) annually. The average yearly runoff of the Verde is about 1.4 inches (36 mm). Floods occur most frequently in winter or early spring. The largest floods of record occurred in the Salt River in February 1891, which was measured just below the mouth of the Verde River, at a peak flow of 300,000 cubic feet a second. Another great flood occurred in November 1905 when the peak flow at the same point was 96,000 cubic feet per second.

The melting of the snow in the spring contributes substantially to the runoff. Of the total annual runoff in the Salt River, 60 percent occurs between January and April, whereas 15 percent occurs in the summer months between July and September, and in the Verde River basin the percentages for comparable periods are 65 and 15, respectively. Flood stages from winter storms are generally persistent and stream discharge remains high for several days; in contrast, summer floods decline rapidly. The streams have their minimum flows in June or early July just before the summer rainy seasons.

In the Basin and Range lowlands province the precipitation is highest on the mountain ranges which, especially in the eastern part, averages about 30 inches (76 mm) annually. In the western and southwestern part, including the Salt River valley, the precipitation generally is less than 5 inches (13 mm) annually. Streams in the lowlands province are generally perennial in their headwaters, but downstream on the alluvial basins they become intermittent, and farther downstream in the desert areas the streams cease to flow. Where the flow from a large area of the mountain region converges to a narrow outlet before flowing onto the desert, the stream is perennial—though losing water through evaporation and infiltration—fur a consi-

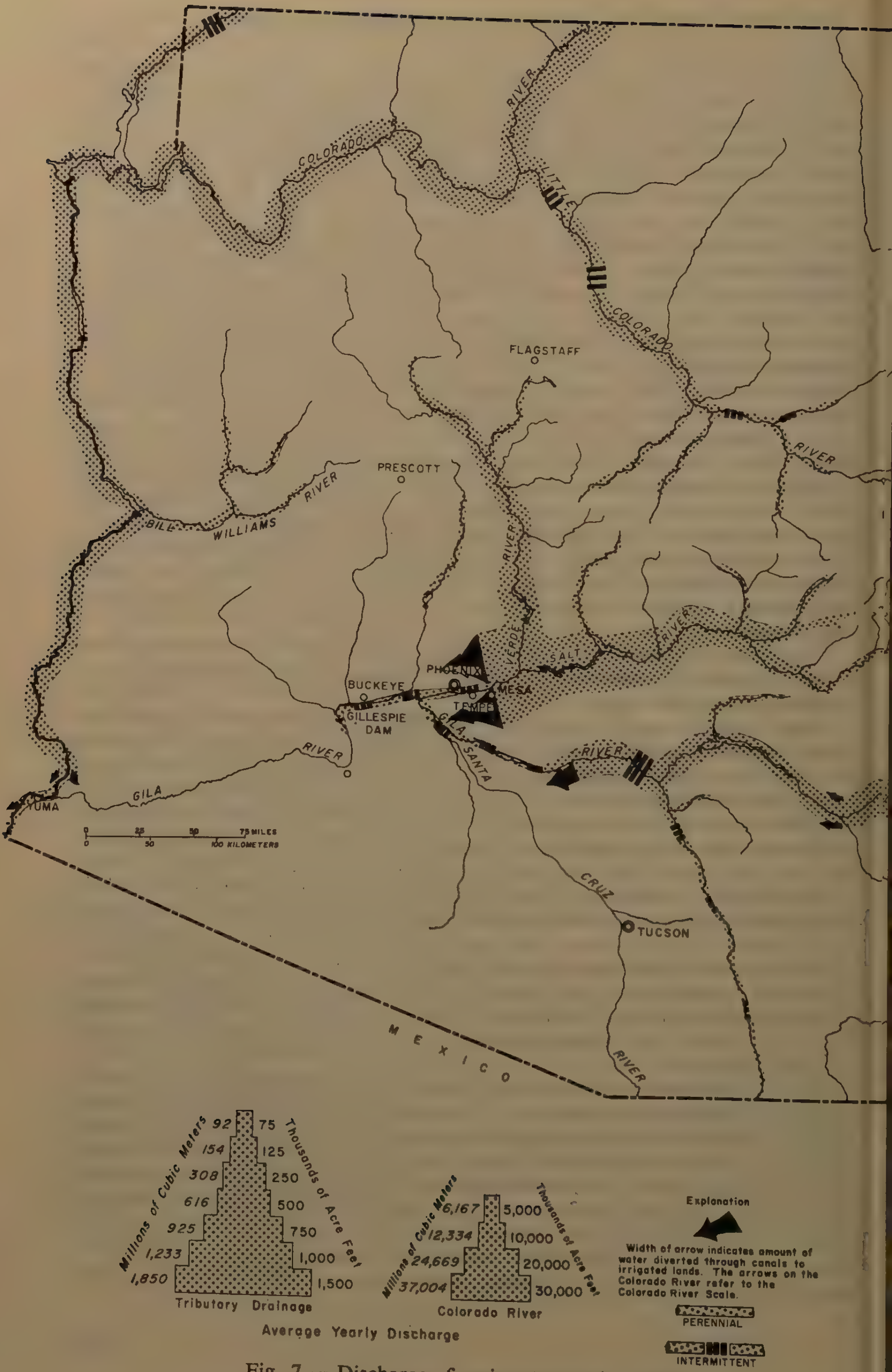


Fig. 7 — Discharge of major streams in Arizona.

derable distance. The Salt and Verde Rivers form such a stream, as the flow combined with the Gila River, under natural conditions, was perennial across the entire desert area. It was the perennial supply of this surface water that made irrigation possible in the Phoenix area.

In the late 1800's prior to the first diversions of water from the Salt River by non-Indian settlers, hay and grain for livestock were freighted from Prescott more than 100 miles over steep mountain roads and desert trails. Many of the supplies for the first sparsely settled community were hauled even greater distances and accordingly, the cost was high and the economic growth of the valley was retarded. A demonstration that food, forage, and fiber could be produced locally through irrigation caused a radical change. Additional canals were constructed, some by the cooperative efforts of the landowners and some by canal companies that expected to profit by delivering surface water to the land. The land nearest the Salt River was put under irrigation first and in general each succeding canal was dug a little farther from the river and roughly parallel to the next most recent canal (see fig. 5). There was no coordinated or general planning for these developments. As settlers moved to the area and took up lands under the homestead acts, a demand for irrigation water resulted and a new canal would be constructed to satisfy this demand.

Except for records of the diversions in some of the canals by measuring the head over the wiers, there were essentially no streamflow records and there was little knowledge of the variability or seasonal distribution of the water supply during the early period of irrigation. Snowmelt from the high altitudes in the mountainous regions resulted in heavy spring runoff, which was generally adequate to produce grain crops. Even base flow during the summer months was sufficient to supply the first few canals. However, as more and more canals were constructed the demand for water, particularly during low flow periods, increased greatly.

All the irrigated lands on the north side of the river could have been watered from the Arizona Canal and its laterals; instead six canals were utilized. The return flow from canal leakage and irrigation waste were the principal sources of water on which the lower canals depended for their low-water flow. Nevertheless, the multiplicity of canals provided an environment for the development of disputes over water rights.

Despite annual and seasonal variations in runoff and occasional shortages, irrigation in the Salt River valley was fairly stable and generally prosperous until the 1890's. Then 6 successive years of drought, together with extreme floods that washed out the diversion works, wiped out most of the progress of the preceding 30 years. Lack of water caused many farmers to abandon their lands and it seemed that most of the valley might revert to desert. The only hope of a permanent irrigation agriculture in the Salt River valley seemed to rest upon developing a dependable supply of water through upstream storage of surplus flows.

The bringing together of the many diverse interests in the Salt River valley in a cooperative effort, the attemps to obtain Federal assistance in construction of water-storage projects, the establishment of the U. S. Reclamation Service, and the organization of the Salt River Valley Water Users' Association were all highly important to the development of the surface-water supplies of Salt River basin. The Salt River Valley Water Users' Association came into being to provide the local management needed to negotiate with the Federal government and to handle local affairs of the project. The only way the Association could operate effectively was to develop equal priorities for all water rights within the project and to make these rights appurtenant to the land. The submerging of individual interests for the benefit of the whole was one of the truly significant developments of the time.

The U. S. Geological Survey began its investigations of the water supply of western United States in 1888. One of the objectives of these investigations was to determine the total annual discharge of water from the basins and the distribution of that discharge through the year. By 1901, some 13 years of streamflow record had been obtained on the Salt and Verde Rivers. Much of this was not record as we consider it today. Short term records obtained at on elocation were transferred to another by «reduction» methods, in which a coefficient representing differences in drainage areas was applied. In other instances computed «proportions of the Salt and Verde River discharged by the Salt River» were used to extend the records. Some of the methods used were ingenious; however, the results were not of a high order of precision. The annual records as published by the Geological Survey are summarized in Table 2. Additional investigations by the Geological Survey in the Salt River basin during the period prior to 1902 included surveys of reservoir sites, core drilling at these sites, determination of reservoir capacities, operational studies, and preliminary design of the dams. With passage of the Reclamation Act of 1902, the preliminary investigations had been largely completed leaving only final design and construction yet to be accomplished.

TABLE 2

Estimated annual discharge of Verde River near Bartlett Dam and Salt River near Roosevelt Lake (1889-1901)

Year	Verde River		Salt River	
	Thoussands of acre-feet	Million cubic meters	Thousands of acre-feet	Million cubic meters
1889	743	916	1,027	1.267
1890	1,187	1.464	1,362	1.680
1891	1,372	1.692	1,739	2.145
1892	130	160	168	207
1893	297	366	789	973
1894	188	232	245	302
1895	763	941	866	1.068
1896	294	362	399	492
1897	514	634	836	1.031
1898	226	279	291	359
1899	217	268	262	323
1900	167	206	153	189
1901	302	372	477	588
Mean	492	607	663	818

Theodore Roosevelt Dam was completed in 1911, with total capacity of 1,382,000 acre-feet (1.705 million m³). As originally conceived, the reservoir behind Theodore Roosevelt Dam would provide all the storage required for an irrigation project on the basis of annual diversions of 660,000 acre-feet (814 million m³). The available water supply under the original concept would consist of natural flow of the Verde River supplemented by storage releases from Roosevelt Lake as needed.

By 1915 Roosevelt Lake had been filled and during the year it was necessary to spill 448,000 acre-feet (553 million m³) of water. The year 1916 was exceptionally wet and the reservoir spilled 1,760,000 acre-feet (2.171 million m³). This was followed by spills of 64,400 acre-feet (79 million m³) in 1917 and 611,000 acre-feet (754 million m³) in 1920. On the basis of this early operation additional storage was clearly desirable.

Accordingly, in 1923 construction of a series of dams was started on the main river. Mormon Flat Dam constructed during 1923-25 added 58,000 acre-feet (72 million m³) of storage; Horse Mesa Dam (1924-27) added 245,000 acre-feet (302 million m³), and Stewart Mountain Dam (1928-30) added 70,000 acre-feet (86 million m³). On the Verde River, Bartlett Dam, completed in 1939 and Horseshoe Dam completed in 1945 added 179,500 acre-feet (221 million m³) and 142,800 acre-feet (176 million m³), respectively, to the upstream storage. In 1941, which was an unusually wet year, Stewart Mountain Dam spilled 160,700 acre-feet (198 million m³) and Bartlett Dam spilled 625,500 acre-feet (772 million m³). As a result of this additional storage the irrigated acreage served by the Salt River Project was increased from about 160,000 acres (65.000 hectares) to about 240,000 acres (97.000 hectares).

A proposal for a large increase in irrigated land never materialized, however, when government aid for the Paradise Verde Project was denied after investigation in 1933 and 1934. Thus the Salt River Valley Project fell heir to rights to the Verde-River, which were senior to many of those in the Salt River Project.

Fig. 8, which shows the annual discharge of the Gila, Salt, and Verde Rivers, for the entire periods of record, indicates the extreme annual variation in flow. The early period of record from about 1890 to 1901 were the only discharge date available for planning the irrigation project, and a part of these records were synthesized.

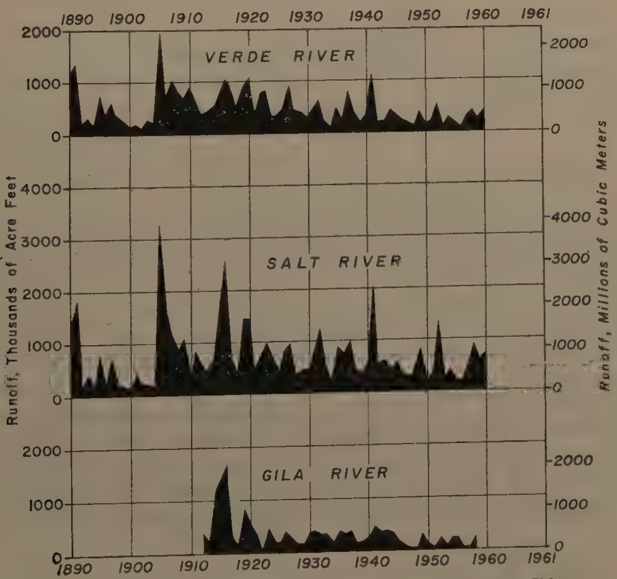


Fig. 8 — Annual discharge of Gila, Salt and Verde Rivers.

The early records indicated a combined average annual discharge of the Salt and Verde Rivers of about 1,150,000 acre-feet (1.419 million m^3). The longer term pattern shows a combined discharge of the two streams of about 1,200,000 acre-feet (1.480 million m^3). Because of the variability the close agreement between short-term records and long-term records was fortuitous, and the water records used to design the original project were adequate only by chance. By the time the additional reservoirs were constructed, streamflow records were available to portray a much more accurate pattern of hydrologic behavior of the Salt and Verde Rivers. The basic problems of the Salt River Project stem from the variation in streamflow. Although reservoirs will continue to spill at intervals, additional storage will not yield any water to be carried over into drought periods. Evaporation from new areas of exposed water surface would exceed any gains from construction of additional storage works.

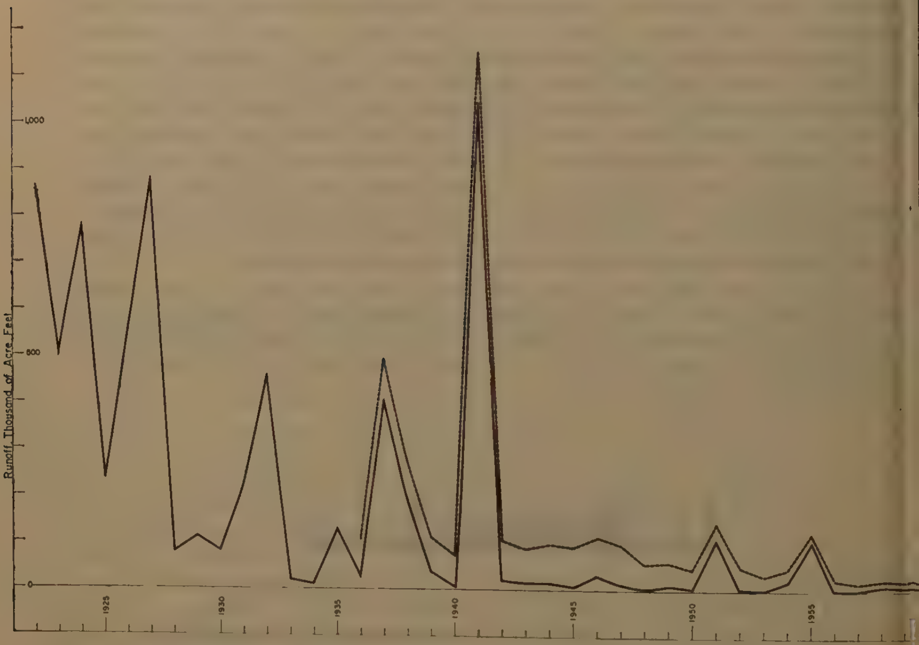


Fig. 9 — Discharge at Gillespie Dam. (The dashed line represents the total flow and the solid line the total flow less the diversion through the Entreprise Canal.)

The effect of the storage of water in the reservoirs in the Salt and Verde Rivers, and the consumption of water by irrigation in the Phoenix area, is reflected in the graph of the discharge of the Gila River at Gillespie Dam. (See fig. 9.) The discharge past Gillespie Dam represents the flow out of the alluvial basin in the Phoenix area. The progressive decline of discharge represents primarily the conversion of liquid outflow to discharge as vapor—through evaporation and transpiration—in the irrigated areas in the Salt and Gila River valleys in and near Phoenix.

During the entire period of operation of the project there have been a few times when the amount of surface water in storage has been seriously low; nevertheless, the reservoir system has never been empty. However, the surface-water resources in the Salt River valley area are fully utilized and have been since early in the irrigation development. Thus, the expansion of irrigation after the early period of surface-water development was dependent on the development of the ground-water resources.

3. THE INTERMEDIATE PERIOD—THE INTERRELATIONSHIP BETWEEN SURFACE WATER AND GROUND WATER

Under natural conditions, prior to water development by man, the height of the water table in the alluvial material in the Salt River valley area was controlled primarily by the altitude of the stream beds of the Salt and Gila Rivers and the geologic barriers or bedrock constrictions in the vicinity of Tempe and near Gillespie Dam. (See fig. 10.) These constrictions caused ground-water discharge to the stream channels. The slope of the land surface between the surrounding mountain fronts and the Salt and Gila Rivers was greater than the water-table gradient, hence the depth to water level increased progressively away from the stream beds toward the mountains.

Ground-water discharged to the stream bed at Tempe was utilized as one of the principal sources of water for irrigation by the prehistoric Indians from 800 to 1400 A.D., when the Indians abandoned the area. No one knows with certainty why this extensive irrigation system was abandoned, but it appears likely that it resulted from waterlogging. The Indians did not have the means of lowering the water table by wells and pumping equipment, but it appears they did take some measures to circumvent the waterlogging problem. Fig. 10 shows the approximate altitude of the canals constructed by the prehistoric Indians in the area west of Tempe. The altitude of the various canals suggests that they were constructed at progressively higher altitudes in order to avoid the waterlogged areas. Although this practice extended the life of the irrigation system, it was finally limited by the altitude of the stream bed at the bedrock construction at Tempe; when this point was reached, no more new land could be brought under irrigation.

In the early 1900's, approximately 500 years after the Hohokam Indians abandoned the area, the application of surface water from the several irrigation projects again caused a rise in the water table. Fig. 11 shows that the principal areas of shallow water table in 1903 were largely confined to the area adjacent to the Salt River west of Phoenix and east of Tempe. In a substantial part of the area the water table was more than 50 feet below the land surface.

By 1920, only about 10 years after the completion of Roosevelt Dam, the areas of shallow water table and accompanying waterlogging had expanded greatly. Fig. 12 shows that in 1920 the water table was 10 feet or less below the land surface in about 30 percent of the area, and in no part of the area was the water table more than 50 feet. This was a decided contrast to the conditions that existed in 1903 and shows that a large increase in ground water had occurred. Although it is likely that most of this rise in the water table was caused by leakage from canals and laterals, it is possible that a substantial part was caused by infiltration from the rivers into the shallow aquifer material. During much of the period from 1903 to 1920 the discharge of the rivers was abnormally high. The rise in water levels and resulting waterlogging showed clearly that the surface-water system and the ground-water system are intimately related and thus changes in one cause changes in the other.

The changes in the surface-water system resulting from upstream storage of water, and the application of that water on the land downstream, produced a

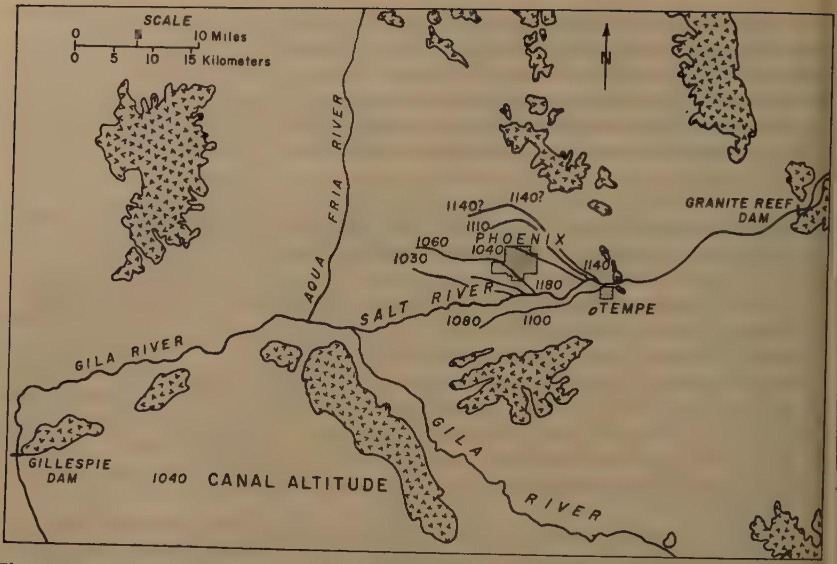


Fig. 10 — Altitude of prehistoric canals and location of bedrock outcrops in Salt River valley area.

decrease in outflow from the basin through streams, but an increase in discharge through vapor transport in the irrigated area and an increase in ground water in storage in the system. The ground-water system, previously in balance under natural conditions, thus had to conduct and discharge increased quantities of water due to infiltration in the irrigated areas. Inasmuch as flow in an aquifer material is dominantly a frictional process, a high potential or head is required to conduct a given quantity of water in contrast to that of a surface stream. In other words, the combined surface and ground-water systems, under the changes imposed by man, had to discharge the liquid water in a much more inefficient manner than under natural undisturbed conditions. The changes in the ground-water system to accomplish this increased requirement consisted of steepening of the hydraulic gradient which could only be brought about by a rise in the water table

Inasmuch as the surface water was adequate to supply all of the land that was under irrigation, the shallow ground water was a serious problem. The prehistoric Indians had attempted to solve this problem by constructing canals at progressively higher altitudes. Conditions in the 1900's, however, were vastly different, as effective well-drilling techniques, efficient pumping equipment, and cheaper sources of power had been developed; thus the means were available to correct the situation. Moreover, the shallow ground water which was considered a troublesome problem now became an attractive resource for those outside of the Salt River Valley Project area.

Accordingly, the irrigation districts to the west of the Salt River Valley Project area, in the Buckeye area, between Gillespie Dam and the Aqua Fria River, proposed the development and transportation of the shallow ground water by means of wells and canals. The area west of the Salt River Valley Project area had no surface-water supply and the ground water was poor in chemical quality. (See fig. 13.) Wells and canals were constructed to convey the ground water pumped. The pumping of ground water in the shallow water table areas principally along the R.I.D. canal

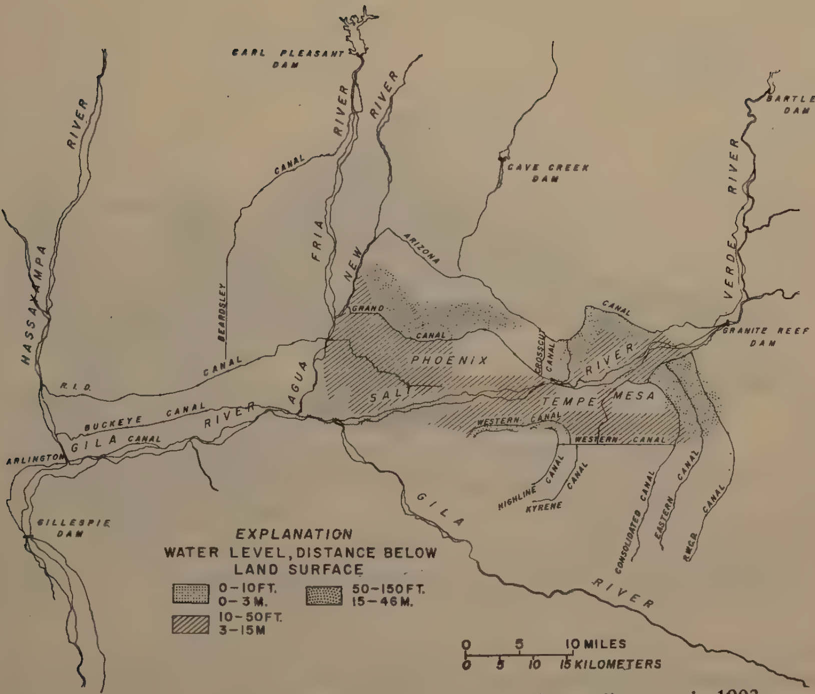


Fig. 11 — Depth to water table in the Salt River valley area in 1903.

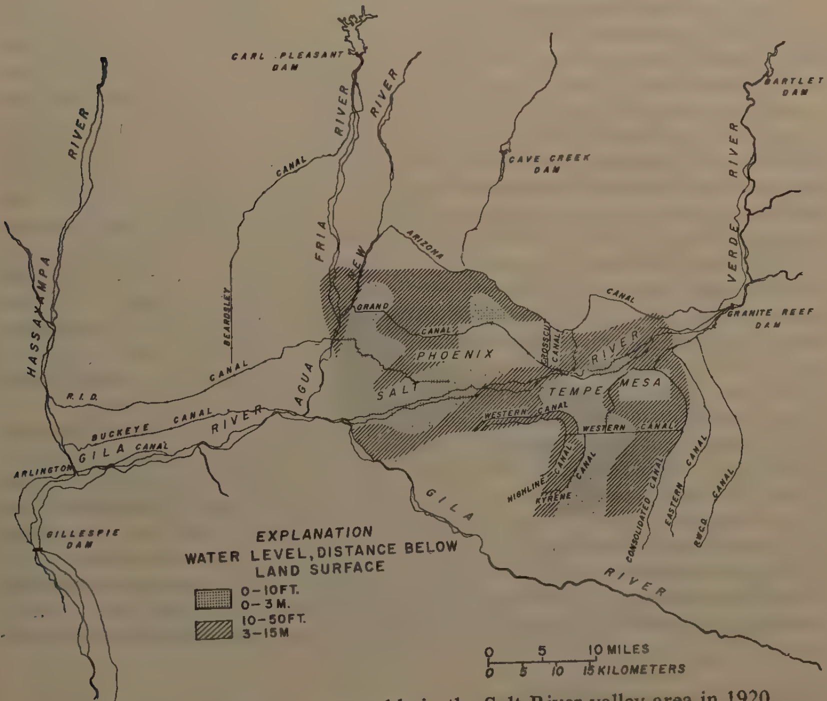


Fig. 12 — Depth to water table in the Salt River valley area in 1920

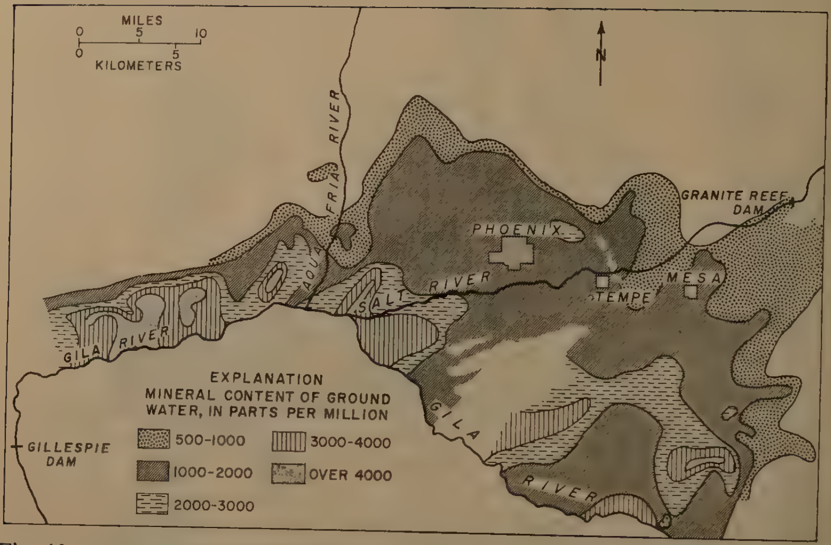


Fig. 13 — Map of Salt River valley area showing distribution of mineral content of ground water.

between Phoenix and the Aqua Fria River, caused a lowering of the water table and provided water for irrigation of a large area outside of the Salt River Project area.

This successful development of ground water for irrigation in the Salt River valley area demonstrated the practicability of such a source of water and this and the progressive increase in value of farm products were incentives for others to develop ground-water supplies from greater lifts. As a result wells were drilled farther upslope toward the mountains. Even in those areas, at a substantial distance from the waterlogged areas, the water table had risen substantially due to recharge from the Salt River Project canals, and as a result it became economically feasible to develop ground-water supplies for irrigation. Thus the area to the north of Phoenix outside of the project area became an attractive area for development and was open to anyone.

The pumping of ground water spread rapidly and by 1945 the resulting lowering of water levels had practically eliminated the waterlogged areas. (See fig. 14.) The water that had infiltrated from the canals and streams prior to ground-water development was to some extent considered a waste and the accompanying rise in water levels a serious problem, but with the pumping of ground water a substantial part of this water was recovered and used to irrigate new land.

It is difficult to determine just what quantity of water is represented by this water whose source was from the surface-water supply. Certainly leakage from unlined canals and ditches in alluvial material such as those in the Salt River valley area can be appreciable. For example, tests made in the Safford valley in eastern Arizona show that about 25 percent of the water applied to the land infiltrated to the ground-water reservoir. Whether or not a similar percentage of infiltration occurs in the Salt River valley area is not known, but in any event it appears that the accumulation over a period of years can amount to a substantial supply of water. Fig. 15, which includes a graph of the average depth to water level in a large part of the Salt River

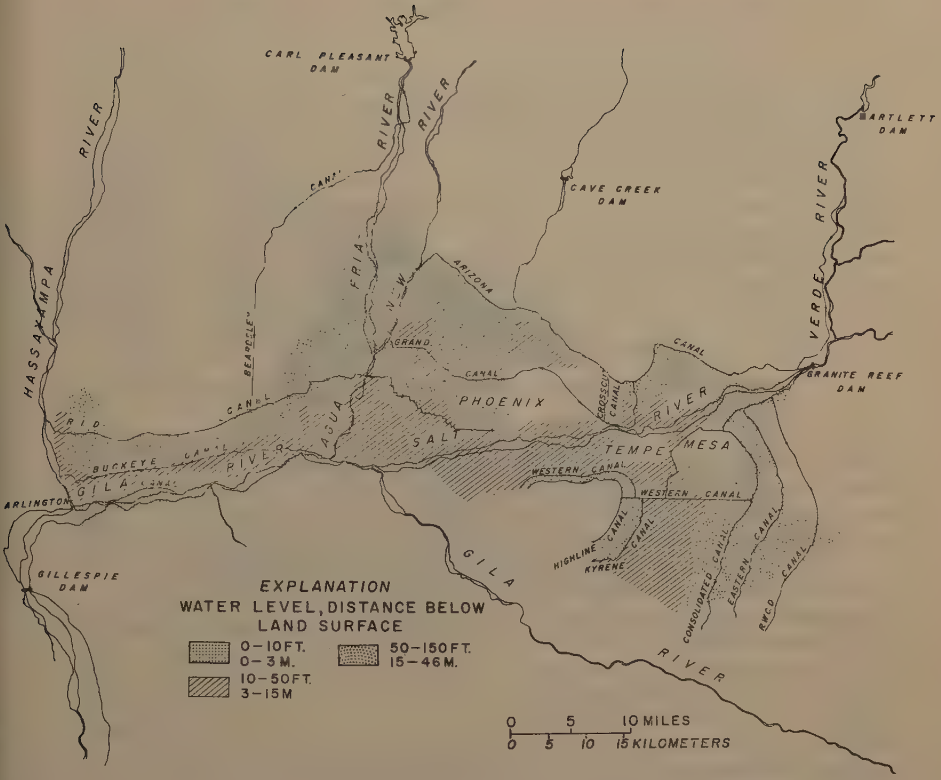


Fig. 14 — Depth to water table in the Salt River valley area in 1945.

valley area, shows well the progressive rise of water level between 1903 and 1920 of about 30 feet (9.2 m). Fig. 16, profiles of the water table across the Salt River valley in the vicinity of Phoenix, shows the wide lateral extent of the rise in water level. It is not known what quantity of water this rise represents but according to the water-level graph it was not until about 1940 that the water level declined to the position it was at in 1903. During those 20 years (1920-1940) the total pumpage was approximately 8,000,000 acre-feet (10.000 million m^3). Of course, during that period part of the ground water pumped and part of the surface water applied infiltrated to the ground-water reservoir.

The interrelationship of the surface and ground-water systems also became evident with the increased pumping of ground water and the accompanying decline in water levels. When the water levels were high, the low-water flow of some of the canals was derived from ground-water inflow, but with the decline in levels this inflow was reduced materially. This has led to a program of lining canals with an impervious seal to prevent loss of water from them.

The manmade disturbance of the surface-water system through construction of reservoirs, canals and ditches, and the application of the water to the land has also produced a significant change in the chemical quality of the ground water in some parts of the Salt River valley area. During each year about 500,000 tons of mineral

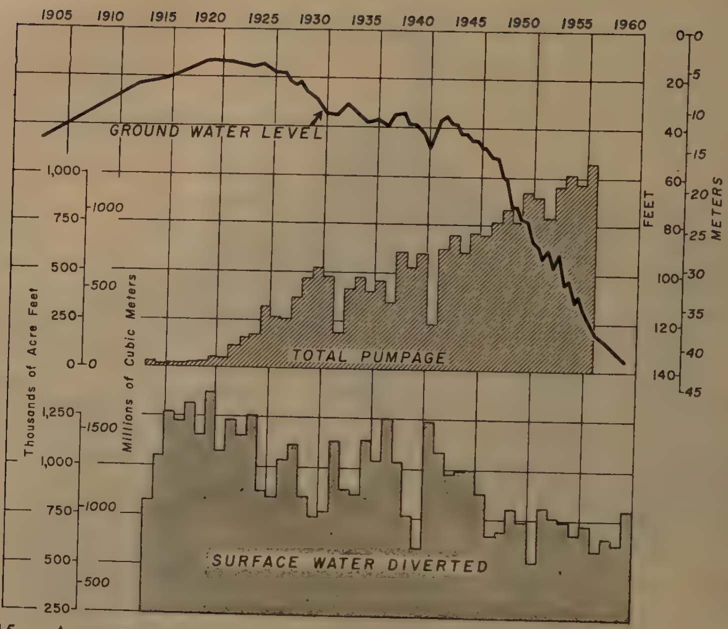


Fig. 15 — Average ground-water level, total ground-water pumpage, and surface water diverted in the Salt River Project area.

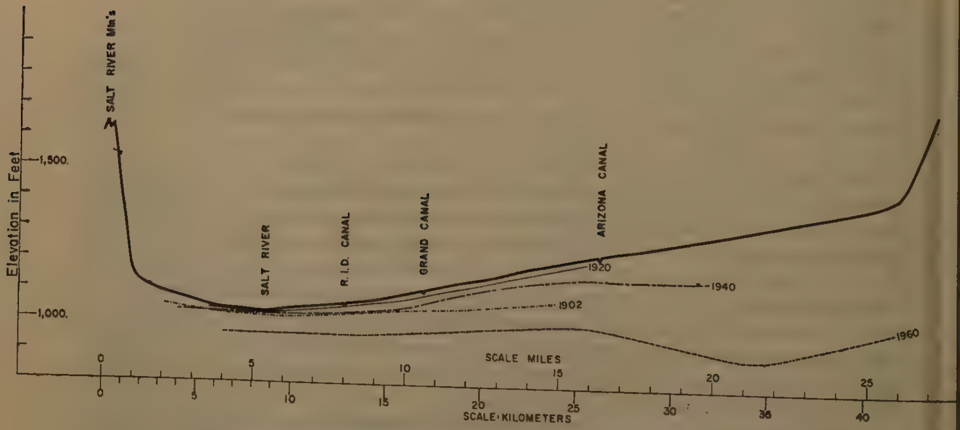


Fig. 16 — Profiles of water table across Salt River valley in vicinity of Phoenix.

salts are carried in the water entering the Salt River valley at Phoenix. Under natural conditions this salt load left the area with the stream discharge at the lower end of the basin. The conversion of the liquid discharge to one of vapor discharge through the evaportranspiration in the irrigated areas has caused the outflow ot salt from the basin to be less than that of the inflow. The result is a progressive accumulation of salt which is represented by an increase in mineral content of the ground water and the soil. This increase has been especially severe in the downstream part of the basin, particularly north of the Gila River between Gillespie Dam and the Aqua Fria River (see fig. 13).

In summary it is evident that the intermediate period of irrigation development during which the interrelationship of the surface and groundwater systems became apparent, was a critical period. If efficient pumps, well-drilling equipment, and power had not been available, the irrigation system might have failed just as it had for the prehistoric Indians some 500 years previous. But the technological advances and development of a fairly stable economy in the area made it possible and feasible to develop an entirely new source of supply. The magnitude of this new supply appeared tremendous, and this, in addition to the increasingly favorable agricultural economy, led to the modern period—the extensive development of the groundwater supplies.

4. THE MODERN PERIOD—GROUND-WATER DEVELOPMENT

Ground water was used in the Salt River valley area as early as the turn of the century, but the methods of well construction and pumping used then differed considerably from those in use today. The early wells ordinarily were hand dug to shallow depths, were of large diameter, and the water was withdrawn by bucket-lift equipment. Today wells are commonly drilled to depths of more than a thousand feet and are equipped with large-capacity pumps operated by powerful motors.

Just prior to World War II, the maximum economical pumping lift throughout southwestern Arizona was considered to be about 175 feet (53 m); today wells with lifts greater than 400 feet (122 m) are common. Electric or diesel motors ranging from 200- to 300-horsepower are required to pump water at an adequate rate from these greater depths and after about 1950, the use of 300-horsepower motors became common.

The extensive development of ground water during this modern period was not only stimulated by the availability of equipment, power, and a favorable economy; there was also a general impression that the quantity of ground water stored in the alluvial basins was so great as to practically constitute an unlimited supply. Moreover, because the buried relief along the boundary between the alluvium of the basins and the bedrock of the mountains is commonly steep, in part due to near vertical faults, wells drilled within about a mile of the hardrock outcrops commonly do not reach bedrock even at depths as great as 1,000 feet (305 m). The steep lateral boundaries of the alluvial material suggest that the water table could be lowered to great depths without diminishing the areal extent of the saturated material.

The principal factors that limit the capacity of an aquifer system are the lithology and stratigraphy of the alluvial material and the shape and size of the basin. The quantity of natural discharge from an aquifer system, such as in the Salt River valley area, is determined primarily by the size and shape of the discharge area and the character of the materials there. Thus the nature of the discharge area controls the rate of natural flow through the aquifer system. These concepts will be elaborated in the following discussion.

One of the most important factors is the physical character of the alluvial material underlying the Salt River valley. The deepest deposits are coarse; these are overlain by lake deposits consisting mostly of thick layers of clay. The clay generally occurs in a zone from about 1,200 to 600 feet (365 to 185 m) below the land surface. (See fig. 17). Apparently the lakes in this area were at a fairly uniform elevation because the clay section is at about the same elevation in different basins. This clay zone is of low permeability, but both above and below it the alluvium generally is coarser and has a high permeability. The upper layer, which forms a water-table aquifer, is about two or three times more permeable than the lower, which forms an artesian aquifer. The thickness of the lower aquifer is not known but some wells have been drilled as much as 2,500 feet in the alluvial basins without reaching bedrock.

Large numbers of nearly impermeable clay lenses and layers also occur within the aquifers in the Salt River valley area as well as in other areas in southwestern Arizona, but to determine accurately those parts of the aquifers that yield water would require detailed mapping of the clay bodies and this would be complicated and difficult. Such mapping has not yet been done and because detailed well data are not avilable, it is not likely to be done in the near future. Hydrologic studies in the area generally have related the withdrawal of water to the decline in water levels without knowledge of the distribution of the clay bodies within the aquifers. Consequently, it has not been possible to foretell accurately the amount of water that would be obtained from different depth zones.

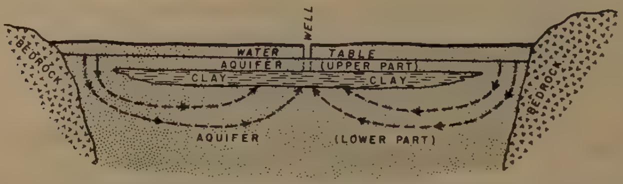


Fig. 17 — Idealized cross section of alluvial basin in southwestern Arizona

The steep lateral boundaries of the alluvium of the Salt River valley have been described. However, not all the boundaries are steep; particularly on the north and east sides of some ranges, the bedrock slopes gently and the alluvium thickens gradually toward the central parts of the basin. Such areas, however, form only a small part of the Salt River valley. Furthermore, the configuration of the buried bedrock surface below the alluvium is almost as irregular as that of the exposed bedrock. These irregularities determine local thickness of valley fill.

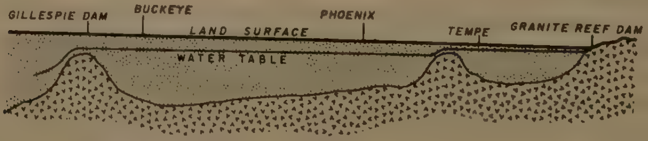


Fig. 18 — Schematic diagram showing effect of rock barriers on position of water table.

Before pumping began in the Salt River valley, the position of the water table was controlled primarily by the elevation of the rim of the relatively impermeable rock barriers over which water must pass to leave the basin. (See fig. 18.) That level can be generalized as a plane surface marking the upper surface of the impounded ground water, extending throughout the aquifer system.

The manner in which underground impermeable rock barriers influenced irrigation during the intermediate period of development is described briefly in the preceding section. The presence or absence of such barriers continued to be important in the extensive development of ground-water supplies during the modern period.

In areas where there are no nearby shallow underground barriers, the depth to water is controlled by barriers farther downstream. In fig. 18, hypothetically, if the barrier at Tempe did not exist, or did not prevent the movement of water, the depth to water at Tempe would be controlled by the barrier at Gillespie Dam. As a result, the depth to water at Tempe would be greater, the saturated thickness of alluvium would be smaller and ground-water development would be less feasible than now. Similar conditions are common in southwest Arizona. In one of the tributary valleys of the Santa Cruz River, a shallow bedrock barrier at the lower end of the valley maintains the water table at a depth of about 100 feet; at the upper end of the valley, about 40 miles to the south, the depth to water is nearly 600 feet, in spite of two areas where the valley becomes somewhat constricted or bedrock crops out discontinuously across the valley. Here the apparent barriers do not act to hold up the water level. Obviously, the volume of water in storage in this valley is less than it would be if the shallow bedrock at the two places formed barriers, and thus raised the water level to two successively higher planes.

Barriers not only act to hold up the water level behind them, they also hold up the level of the water that moves over them. Where the barrier is extensive, it may maintain shallow water levels between adjacent areas of deeper water levels. In the Santa Cruz valley a 2 to 4 mile wide shelf of shallow bedrock extends about 10 miles between mountains south and north of Casa Grande. Above this shelf, the depth to water averages about 75 feet; to the west, downgradient, the depths to water within 2 miles drop off to more than 150 feet; and to the east, upgradient, the depth to water increases more gradually, and only becomes as much as 150 feet in about 10 miles.

During periods of recharge the water table rises above the level or plane established by the lip of the basin. The amount of rise at any point is determined by the quantity of ground water flowing past the point and the transmissibility of the aquifer between that point and the outlet for the ground-water discharge. The hydraulic gradient toward the locality of discharge is directly proportional to the amount of ground water flowing and inversely proportional to the transmissibility.

In the Salt River valley area and other areas in southwestern Arizona the aquifers are recharged two ways. One is by infiltration of rainfall on the area; the other is by infiltration of surface water. The amount of recharge from precipitation is negligible because the soil-moisture deficiency is generally high enough to prevent infiltration to the water table. Infiltration of surface water occurs where a river flows across alluvial valleys. Most streams emerge from the adjacent mountains, flow across the alluvial basin, and discharge generally into other streams. Water can move downward to the water table and through the aquifer to discharge points where it may return to the river. The more rapid the recharge, the more rapid the rate of ground-water flow required to move the water across the basin; this is reflected in steeper hydraulic gradients.

The interrelations between barrier height, hydraulic gradient, original ground-water levels throughout the region, depth to water below land surface, and the permeability are of great importance. The permeability of the aquifer material bears importantly upon the position of the hydraulic gradient and water table. The lower the permeability, the steeper the water table will be and thus the shallower the initial pumping lift. However, this beneficial feature is more apparent than real with respect to ground-water development. Although shallower water levels prevail in the original or natural state, the pumping of wells reveals the short-lived nature of this advantage. To move water to a well at a certain rate—to sustain a desired pumping rate—requires steeper hydraulic gradients in material of lower permeability. This in turn means greater drawdowns or increased pumping lifts in the pumped wells, and the increased drawdowns may be the controlling feature in the amount of water that may be pumped economically from an area.

The development of ground water in the Salt River valley area and in other parts of southwestern Arizona has been unique in the sense that wells were drilled throughout the area within a relatively short period of time. Accordingly, for the most part pumpage was imposed over the entire region in a fairly uniform pattern. In relation to the long-term hydrologic history of the basin, the spread of ground-water pumping may be considered instantaneous, which simplifies the analysis of the pumping effects. Instead of attempting to identify cones of depression associated with individual pumped wells, and in some manner summing these complex effects, it is generally necessary only to analyse the aquifer system as though there were a uniformally distributed lowering of water levels. Although this is simple in principle, the actual manner in which the aquifer is depleted is more complex.

The controls on the development of ground water may be reflected in maps such as those showing water-table and drawdown contours. Some of these maps have been prepared, but others have not been attempted. (See table 3.) The significance of water-table maps has been discussed already. Maps showing the magnitude of drawdowns reflect the rate of pumping and the transmissibility of the aquifer; that is, if the pumpage is known, configuration of the contours of equal decline reflects differences in the permeability of the material. If drawdowns are measured at succeeding intervals of time, they increase progressively as the storage within the aquifer is depleted. Maps showing the difference in drawdowns between two successive measurements also shows the effect of lithologic and stratigraphic controls and will give an indication of the presence of clay layers. Finally if the differences between two successive maps of the previous type are plotted on a map, the configuration and magnitude of the resulting contours will indicate the differences in transmissibility and storage coefficient as the water table is lowered.

TABLE 3

Types of hydrologic maps which reflect controls on ground water in the alluvial basins in southwestern Arizona

Type of Map	Types of Controls Reflected
Water-table contour map	Lithology and stratigraphy (permeability and transmissibility) Rock boundaries (presence of barriers) Quantity of constant discharge
Drawdown map (Difference between two water-table maps)	Lithology and stratigraphy Quantity of pumpage
Drawdown difference map (Difference between two drawdown maps)	Change in lithology and stratigraphy (also storage capacity—percent of total region along the water table that yields water) Change pumping rate
Second drawdown difference map (Difference between two succeeding drawdown difference maps)	Variation in the change in the lithology and stratigraphy Variation in the change in pumping rate

Wherever the distribution of wells in the Salt River valley does not extend to the edges of the aquifer a more complicated ground-water flow system prevails. The water movement then involves in part upward flow through a laterally extensive body of clay. The general features of such a flow system are illustrated in fig. 17. Pumping of wells tapping only the water-table aquifer near the center of the region, cause local lowering of the water table. Water is thus induced to move from the deep-seated artesian aquifer upward through the clay body. To replace this, water migrates in the artesian aquifer from the outer parts of the region, where in turn water moves downward through the overlying clays. The downward movement entails some decline in head and the amount of water in storage in the overlying water-table aquifer. Because of the low permeabilities along this complex path, the movement of water is very slow and is accompanied by high losses in head. Another factor that contributes to the regional uniform lowering of water levels is the occurrence of zones of highly permeable gravels in the aquifer, which function as water-collecting galleries for the wells.

The quantity of water pumped by itself means little in terms of the long-term supply from an aquifer. A much more significant factor is the amount of liquid water evaporated and returned to the atmosphere. This water is lost to the system; the remainder of the water pumped conceivably may return to the aquifer. In irrigated areas the time required for water to move from the land surface to the water table commonly is very long. In its downward path to the ground-water reservoir the water must move around the many clay lenses and layers. Thus a large amount of water may be in transient storage between the land surface and the water table. In many irrigated areas the recharge water comes from pumped wells rather than from a surface-water supply; in the Salt River valley area, however, the recharge water includes water from local surface-water irrigation.

Studies of the flow of soil moisture have shown that for significant amounts of water to move the porous medium, unless the void spaces are large, must be nearly saturated. In the arid environment existing before irrigation and pumping started in the Salt River valley the materials between the land surface and the water table were deficient in moisture except below the stream beds. With the application of irrigation water, however, the top of the soil column above the aquifer became very moist. Where before irrigation started not more than 7 inches (178 mm) of rain fell annually in the area, after irrigation began as much as 4 feet (1.4 m) of water per year were applied to the top of the soil column.

In effect, with irrigation the soil column is exposed to a humid climate contrasting sharply with the previous arid climate. With this change a large amount of water goes into storage in the pore spaces above the water table. And as the pore spaces must be nearly saturated before significant downward movement occurs, then the rate of advance of the water front is less than the rate of decline of the water table. This is particularly true where the distribution of pumpage is of the type in southwestern Arizona. In general the entire area is being pumped and the water level moves downward almost as a plane surface. Inasmuch as the pumping rate far exceeds the recharge from surface water, and it is unlikely that the pumping rate will decrease materially, it is apparent that practically all the water pumped is taken from storage. The development of water supply in the Salt River valley area thus is essentially a mining operation.

At present it is impractical to determine how much water is being recirculated, how much is being evaporated, how much is going into soil-moisture storage, and how much is coming from storage in the aquifer as the water table declines is a difficult problem to answer, and little has been done to identify these separate elements of the problem. Water-table measurements show that a general decline of as much as 75 to 100 feet has occurred in many areas since pumping started. (See fig. 19.)

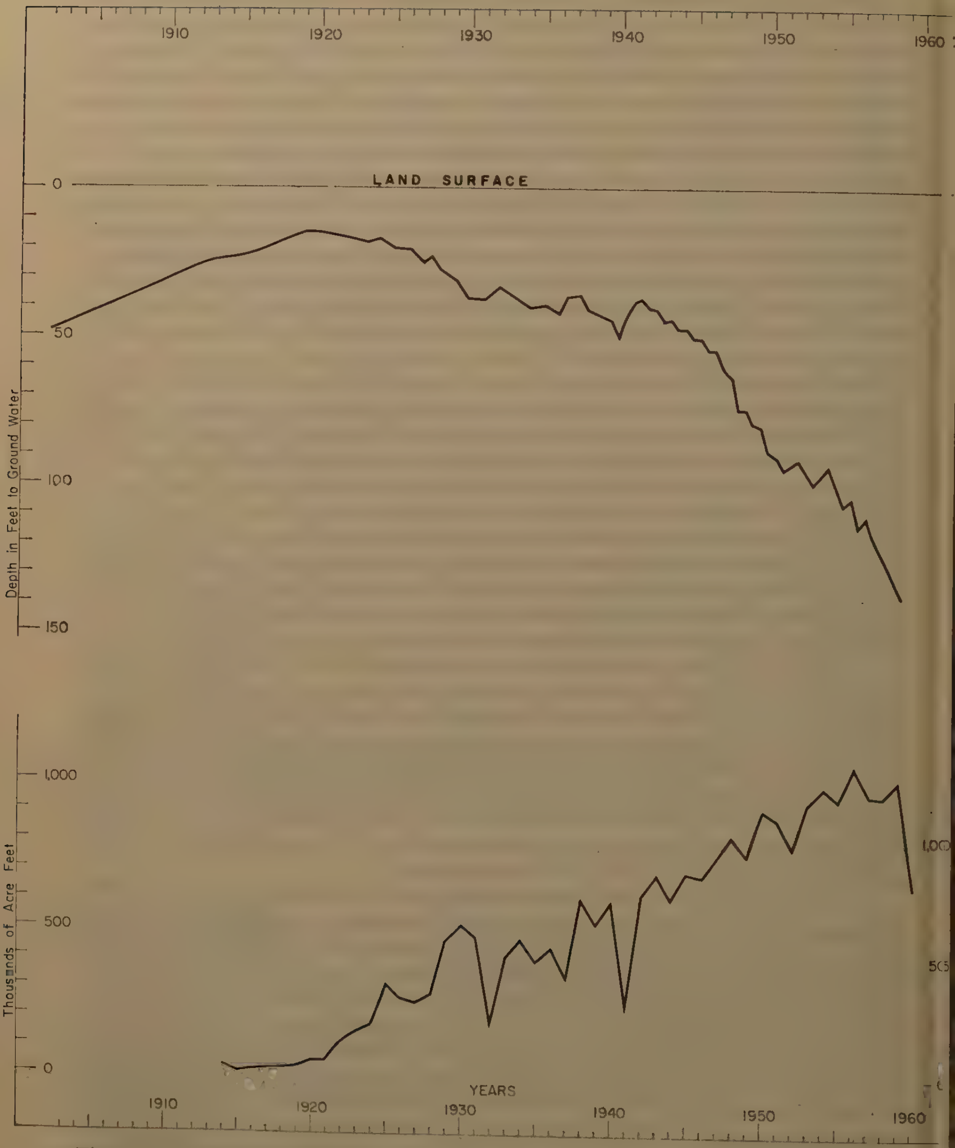


Fig. 19 — Average depth to water level and total pumpage in Salt River valley area.

As the water-table declines the saturated thickness of the aquifer material decreases because a massive clay layer is encountered at depths of about 600 feet and many wells end in the clay; this causes a decline in the yield per unit of drawdown. It might appear that the decline in yield would not occur because much of the water produced by individual wells comes from the thin zones of highly permeable gravels described previously. However, the lowering of head in these thin zones or layers spreads rapidly outward from the well. Water movement towards a well thus occurs in both the vertical and the horizontal planes, and accordingly, the whole aquifer responds to pumpage in proportion to the thickness of the aquifer.

In the past, as wells began to decline in yield they were deepened in the hope of tapping a greater thickness of water-bearing material. Drilling was difficult in the thick clay zone below the water-table aquifer, and most of the deepening operations were terminated without completely penetrating the clay. Had the deepening been continued to depths of 1200 feet and beyond, the deep-seated artesian aquifer would have been tapped and some improvement in well yield might have been realized. Upon completion of the deepening operations the performance of many wells suggested that the yield had been greatly improved. After drilling into the clays, many wells which previously had drawdowns of 150 feet or more showed drawdowns of only 75 feet at an output of 2,000 gallons per minute. The records of the original pumping tests in many of these wells show, however, that the original drawdown was also around 75 feet; the cause of the increases in the drawdown to 150 feet is believed to be related principally to encrustation of the slots of the well casings. Encrustation of the slots severely lowers the wells specific capacity because of the large head losses produced by the movement of water through the restricted openings. During the work involved in the well deepening the pounding of the bit in the casing loosened the encrustations in the slots and the specific capacity seemed to increase. Although the improvement happened to attend the well-deepening process, any technique that jarred free the encrustation would have accomplished the same result.

The deep artesian aquifer yields much less water for a given decline in head than the unconfined aquifer. When water levels in the water-table aquifer have gradually declined to the top of the clay zone the only readily available ground water remaining in storage will be that in the deep artesian aquifer. This ground-water will be under artesian pressure until the water levels are lowered beyond the bottom of the clay zone. In pumping from the artesian aquifer, the decline in artesian head to the bottom of the clay zone presumably would be rapid assuming that little water is yielded by compaction of the aquifer. When it reaches this level, however, dewatering of the aquifer would begin and the coefficient of storage would increase tremendously. In many places this stage of development would require a minimum pumping lift of 1,200 feet (366 m) whereas at present the economically feasible pumping lift is no more than 600 feet (183 m).

The massive clay zone thus is a dominating limit on the development of the ground-water supplies in the Salt River valley and similar areas in southwestern Arizona. Moreover the clay zone would limit the opportunities for returning water to storage in the lower aquifer.

Further development of aquifers in Arizona is proceeding on the only partly substantiated hope that the character of still saturated materials will be similar to that of those already dewatered. However, available information suggests that the nature of the fill will change appreciably, although not enough is known to predict the amount of water in the still saturated materials. As pointed out earlier, hydrologic maps can reflect the controls that have acted on the dewatered part of the system. (See table 3.) But such maps cannot be used to predict the characteristics of the materials that will supply the water for future withdrawal. In other words, much of the data collected now permits the interpretation of what has happened, but it is not the information necessary to make predictions. In order to predict future fluctuations of the water table, if it can be done, it is necessary to know the lithology, stratigraphy, size and shape of the remaining saturated material and the pumpage that will be imposed on the system. The quantity of pumpage can be decided arbitrarily, but, until the geology of the saturated materials is known, future development will proceed primarily on empirical relations.

The future development of aquifers in southwestern Arizona is somewhat indeterminate at this time. It will not be possible to continue pumping water at the present rate indefinitely. However, the length of period in which pumping remains feasible is closely related to and will depend upon the intended water use. The question of the ultimate economic pumping lift enters into the determination of the feasible pumping period. Pumping lifts of as much as 500 feet (153 m) have proved economically feasible in southwestern Arizona; in the San Joaquin Valley of central California pumping from depths as great as 900 feet for irrigation supplies has proved economically sound. However with ground water presently developed primarily for agricultural use, and in the light of present pumping costs and crop values, 500 feet appears to be close to the maximum economic pumping lift in southwestern Arizona. But pumping lifts far beyond this limit appear feasible for domestic or industrial water supplies. To answer the question of how best to use the ground water in the Salt River valley area and elsewhere in southwestern Arizona would require the combined talents of the hydrologist, economist, and sociologist.

5. SUMMARY

Many changes in the pattern of water use in central Arizona have been observed as irrigation development has taken place. The early settlers of European origin were, like the indigenous Indian, dependent on surface-water supplies. Growth during the first 50 years was related to the regulation of the Salt and Gila Rivers and their tributaries. About the time of the first World War, however, the availability of large supplies of ground water in the valleys of central Arizona was recognized. Much of the original ground-water development was associated with the need for drainage in irrigated areas with high water table, but as time went on, ground water from aquifers outside the irrigated areas was developed until today the land irrigated from wells exceeds by a considerable margin the land irrigated with water from surface sources.

Increase in area irrigated from ground-water sources has been closely related to improvements in technology. As more efficient pumps, motors, and sources of power became available, the economic depth of pumping increased. In the middle and late 1920's about 65 feet was considered to be the limit of economic pumping depth for irrigation. Today pumping from depths of 1,000 feet for the irrigation of high-value crops or for municipal use is considered feasible.

The effect of this draft on ground water has been discussed in the preceding sections. The way in which ground-water elevations have declined has been shown. What is essentially the mining of ground water has been discussed. The limited life of many areas dependent on irrigation, in fact the reversion of irrigated land to desert has been noted.

The preceding sections, all covering certain aspects of the utilization of the water resources of central Arizona have had a common purpose. This purpose was to emphasize certain factors which are of prime importance in the use of water whether it be surface water or ground water.

Our fundamental premise is that there is always a balance in the inflow and outflow of water in any area. Sources of inflow are precipitation and movement of water into the area either on the surface or underground. Outflow is by means of evapotranspiration and either surface or underground movement of water. Inflow and outflow must be equal quantitatively or the difference is made up by gain or loss of water in surface or underground storage.

A second premise is that in any arid region of reasonable size, consumptive use of water by man is the conversion of liquid water to water vapor in the process of using it for some purpose. Such a use may be considered beneficial or nonbeneficial, depending on the economic or social return for the loss of water. These points must be emphasized as they are the principal factor that distinguishes the use of water in arid region.

Areas in which water resources are suitable for development by man should be areas of water surplus. Presumably, such areas are those where the outward movement of water, not water vapor, exceeds the inward movement of water either on the surface or underground. However, such a definition in practice in arid regions has proven to be too restrictive. Surplus as a word in such areas is subject to a broad interpretation. In fact, analysis of development in Arizona leads to the conclusion that any water for which there is not an immediate demand is considered surplus.

Thus, a surplus may be due to low demand or an over supply. Insofar as ground water is concerned, any surplus is usually due to lack of demand rather than over supply. Ground water, moving slowly, tends to have the characteristics of a reservoir rather than a flowing stream. In an arid region, the effect of demands on ground water depends on the size of the reservoir because rates of recharge are usually low.

On the other hand, in an arid region, the amount of surface runoff varies greatly with time. Surplus surface water is usually that in excess of requirements of diversion works. It may be excess because of floods or because it occurs in a season of the year with little demand for water. If this water is to be used, it must be regulated. This requires storage, but because of the nature of runoff, we can never completely regulate the flow of a stream. In addition, storage of water in surface reservoirs results in increasing evaporation losses. The maintenance of a favorable salt balance requires that a certain amount of water leave any irrigated area. Thus it is impossible to utilize completely in a beneficial manner the water leaving an area in liquid form.

Any water development usually results in the utilization of some liquid water which in the native state formerly had been converted into water vapor. Diversion of water from a river eliminates some of the normal evapotranspiration losses. Removal of phreatophytes eliminates a drain on ground water and makes liquid water available for capture.

Despite a broad definition of what constitutes surplus, it must be realized that developments based on the utilization of water in storage, either surface or underground, cannot be permanent. Unless storage is replenished, and such is not considered in this generalization, it is obvious that any demand however small will eventually exhaust any water in storage. Such a result is a matter of time.

Thus the efficient use of water in an arid region involves a thorough understanding of the hydrology of an area. By this is meant not only an understanding of the magnitude of the elements of the hydrologic cycle, but the evaluation of the size of reservoirs whether they are surface or underground.

Where demands on water approach the supply, management of the water resource becomes a necessity. In Arizona management of water has been in part by decision and to a large extent by what appears to be accident. The economic factor has had more influence on water-management decisions than the hydrologic factor. Economic factors have not been static. They have changed with time and with social patterns in the development area.

Clearly, therefore, decisions affecting water-resource development must involve many considerations only one of which is the hydrology of the area. However, and this is the point emphasized, all considerations fail unless they are congruent with the hydrologic aspects of the area. The hydrologist has the responsibility of delineating those elements of his field which are important and which must set the boundaries, physically or otherwise, of the development. In this he must exercise great care not to confuse hydrology with something else.

An excellent example is to be found in the central Arizona area. The previous sections have shown that it has been recognized that those areas unaffected by irrigation from the main stream were areas with very low rates of recharge and that most pumping operations were in effect, ways of mining water.

It has also been noted that at the beginning of the development of this area the economic depth of pumping for irrigation was something less than 100 feet. If at that time a decision had been reached to limit the draft on ground water so as to extend its use over a period of some length, very few wells would have been drilled in any aquifer, the reason being the small amount of storage in what appeared to be the economic pumping depth. Thus the rate of development as well as the magnitude of the development of the dependent irrigated land would have been small.

Instead, with no restriction on ground-water use, the economic depth of pumping increased with improved technology. But the improved technology was spurred by the economic return from the development. The result was a considerable expansion of the irrigated area and with it a greater expansion in the population. As was to be expected, the resultant overdraft on ground-water storage was very heavy. In some areas pumping lifts became uneconomic and land was forced out of agricultural production and more will be forced out in the future for the same reason. It is clear that in the future acreages of land used for agriculture cannot be expected to increase. This effect was, hydrologically speaking, fully predictable.

Increased population, due initially to agricultural development but compounded by a pleasant environment, led to industrial development and a faster rate of population growth. Cities and industry expanded into farmland and low consumptive uses of water supplanted high consumptive uses. Today there is still an adequate supply of water for a growing population if it is not dependent on agriculture.

The dilemma continually facing the hydrologist as an individual is to decide whether restrictions ought or ought not be placed on groundwater use. Restrictions have been placed on surface water. The laws of appropriation have provided a means by which a surface-water supply can be divided among a number of individuals. Should something similar be provided for supplies derived from ground water? The record is not clear. Certainly no answer can be given on hydrologic grounds.

Decisions on how ground water is to be managed will have to be based on a broad understanding of the society of which the water-using areas are a part. This brings up the whole question of social and economic planning, a subject far more difficult than those involving ground-water movement.

Suffice it to say, however, that in the case of the Salt River valley area in central Arizona, at least, lack of restriction on the individual has not operated adversely on the community as a whole. Here, no control over well drilling has been an effective form of management. That this is true under the circumstances peculiar to central Arizona does not mean that such an approach would be uniformly desirable.

Whether a short-lived irrigation development would disrupt the economy of a community would seem to be dependent on the relative importance of the development to the total economy. The West is full of ghost towns left after mines had played out. This fact of mining operations has been accepted as a necessary evil. The general reaction is, however, that while water may be mined if it is the only resource, it should be done under some type of regulation as in New Mexico. New Mexico would like to see its aquifers usable for a minimum period of about 50 years.

The essential difference between a mining operation and pumping water is that water follows no political boundaries. One can imagine the chaos that would result if everyone were free to extract ore from a metal mine at any rate he wished. It is surprising that we mine water, under like methods of operation, as well as we do. We have not managed aquifers like we do oil fields. But the day will come, as it did in the oil business, when management is a necessity.

The fact that hydrologists do not bear the responsibility for making certain fundamental decisions with respect to how the water resource will be managed does not detract from their responsibility in management decisions. Obviously, in the central Arizona case no high-level decisions have been made. But there have been a myriad of small ones. Every pump represents a kind of hydrologic decision and every release from a reservoir represents another. As has already been pointed out, every one of the decisions must be congruent with hydrologic facts if eventual harm is to be avoided.

A decision to drill a well must have as a base an assumption that water exists at certain depths and can be extracted at certain rates. Thus some knowledge of the aquifer is presupposed. A decision to release water from a reservoir is an exercise in probability. What is the chance that water released from storage will be replenished for use in time of need? Records of some kind must be available to describe the flow of the tributary streams. These kinds of decisions and others like them are made so frequently that there are no longer great errors. There are other decisions, however, for which this is not always true.

Earlier it has been mentioned that under maximum use of a water resource some water which had previously been lost is salvaged or made available for use. This is the result of elimination of evapotranspiration opportunity by denying water to a former area of loss. As water becomes scarce and water users more informed, operations have been directed specifically toward water salvage.

These efforts are laudable, but the hydrologist must be certain they are not counted more than once. In central Arizona canals and ditches have been lined to save water. It should be clear that no water is ever saved by this procedure unless water is prevented from escaping to the atmosphere. Lining of canals, laterals, and ditches permits a given amount of water to be conveyed to a larger area of land. This, in itself, may be an adequate justification. But if water lost from canals by seepage is the water that supplies a pump, then water is not salvaged by lining. Furthermore, it is possible that elimination of channels for the drainage and recovery of waste water by their replacement by pipes may cause losses by evaporation from ponded water surfaces.

Considerable attention has been directed toward the use of water by phreatophytes. This is a lesser problem today than it was 40 years ago, even though the type of vegetation has changed and saltcedar (Tamarix Galica) is now the most noticeable species. The lowering of the water table accompanying the development of ground water has done much to eliminate phreatophytic losses and to salvage water. Any further improvement in water salvage will be dependent on two things; First, an ability to deprive undesirable plant species of water now being consumed, and second, an ability to physically capture any water now being wasted. Frankly, in the central Arizona area possibilities for additional salvage in terms of present use do not appear to be great. No salvage of water can be expected unless the areas of loss are known and can be described. Furthermore, no salvage can be expected until the actual body of water, formerly lost, is put to use.

But there are other aspects of the management of central Arizona water which, although not receiving any great amount of attention, should be of considerable interest to hydrologists. This is a by-product of the change from an agricultural to an industrial or municipal use of water. The lesser use of water by municipalities or industries with respect to that for agriculture comes, not from any reduction in demand, but from an increase in the return flow. (This can also be expressed as a reduction in consumptive use). Under agriculture, return flows moved in certain ways. They were picked up by pumps or other diversion canals, and reused either on the initial area or nearby. Under some stages of municipal development, homes and businesses dispose of water wastes through septic tanks and leaching lines. Return flows from these sources are quite similar to those derived from irrigation.

But there comes a time when the return flow from individual users is combined and treated in sewage plants. Effluent from these plants represents a concentration of the return flow from a relatively large portion of the water-using areas. Mass treatment of sewage seriously disrupts the hydrologic patterns of the area. This alone would have serious repercussions. In addition, for aesthetic reasons, there appears to be a disinclination to consider sewage as a vital or even important item in the hydrologic budget.

Apparently, if municipal growth continues, some action will have to be taken to recognize the relation of sewage to maximum use of the water resource. This will involve a number of considerations not all of which are in the field of the hydrologist. One of these will have to be whether centralized treatment of sewage is better than treatment by individual water users. It does not seem likely that the hydrologic aspects of this problem have been considered.

Considering the recent history of the movement of the water table in the Salt River Valley Project, it seems strange how quickly water-logging became a problem. High water tables were widespread throughout the project area less than 10 years after the completion of the main storage dam. It is true that this was a period of high runoff. The question arises as to whether an equivalant rise in ground-water elevations would take place today under like conditions of rainfall and runoff. The answer must be that we do not know, because study of recharge of ground water has not kept pace with study of withdrawal.

Much too little is known about the movement of water through an unsaturated medium but it would seem likely that the concentrated effort to save water by lining canals and ditches has seriously reduced the recharge potential of the area. The increase in depth to ground water has undoubtedly modified adversely the movement of water from natural waterways to the water table. No one has any idea of how much water is in transit through the ground and when it will reach the water table. These unknowns are equivalent in management of a surface-water reservoir, to try to estimate the discharge rate without knowing the inflow or the dead storage. The saving factor in ground-water management, of course, is that the reservoir is very large in relation to the recharge. But this does not excuse the hydrologist from an obligation to fill such gaps in our knowledge.

This briefly summarizes a few of the obvious problems in the management of the water resources of central Arizona. It is evident that all of the problems, hydrologic and economic, have not been solved. However, resource development, in the final analysis, must deal with people with all of their characteristics, good and bad. Results have been reasonably good.

From a technical standpoint, some decisions have been made without a full knowledge of the hydrologic facts. Thus, trouble is likely to be encountered as, sometime in the future, the water-based developments begin to decline. That this has not happened yet does not mean that the determination of hydrologic facts is not necessary. Neither does it mean that overall regulation of limited water resources is not a necessity in an arid region. The best we can say is that the geography, geology, climate, and hydrology of central Arizona have all combined, fortunately, to permit a wide margin for trial and error in management decision.

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